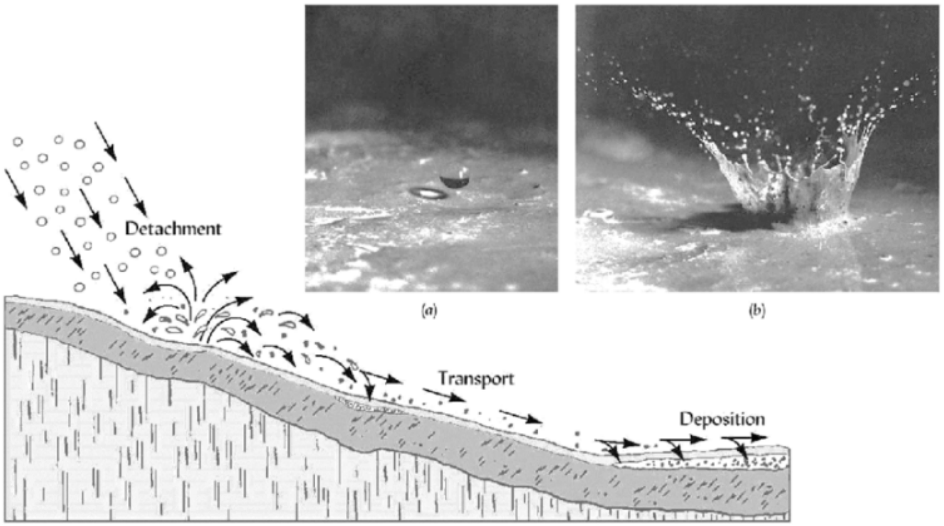
Ultrasonic Machining (USM)

ME312: Manufacturing Technologies - II
Instructor: R K Mittal

Ultrasonic Machining (Nature)

Examples in Nature

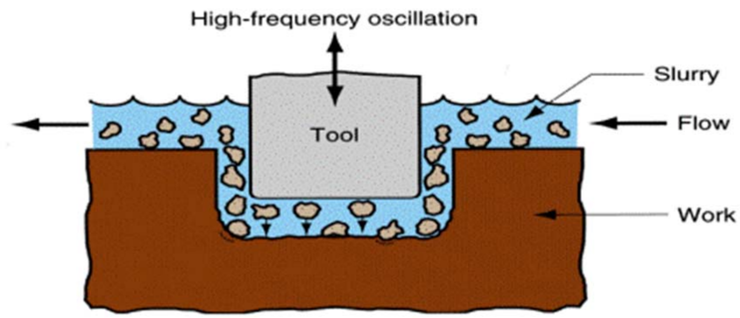


(Bashir et al. 2017)

Link

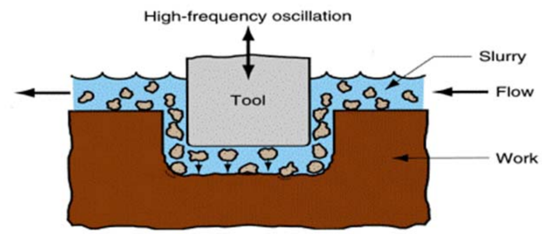
Process Description

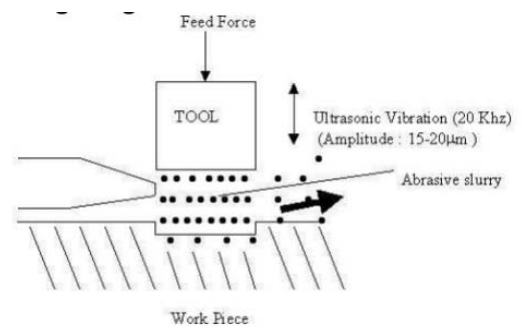
- A mechanical type non-traditional machining process.
- Balamuth first discovered USM in 1945 during ultrasonic grinding of abrasive powders.
- The industrial applications began in the 1950s when the new machine tools appeared.
- Removal of hard and brittle materials (both electrically conductive and non-conductive)
- The tool, which is negative of the workpiece, is vibrated at low amplitude (0.01 to 0.1 mm) and high frequency (greater than 20 kHz)



Process Description

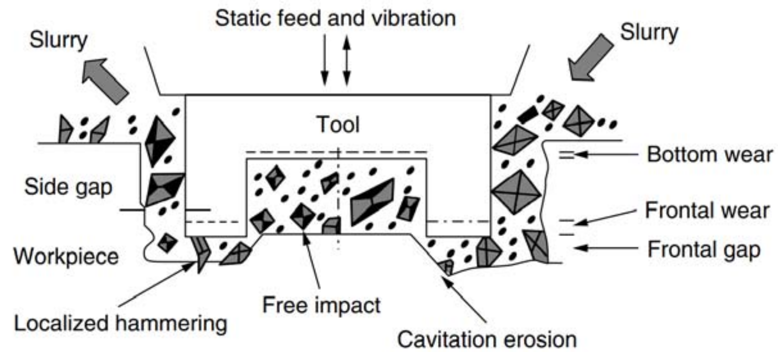
- Abrasive slurry is continuously fed between a soft tool and the workpiece
- Abrasive particles are hammered into the workpiece surface and cause chipping of fine particles from it
- The slurry also carries away the debris from the cutting area
- The tool is gradually moved down maintaining a constant gap of approximately 0.1 mm between the tool and workpiece surface
- Slight pressure on the tool to ensure the fracturing of workpiece
- Abrasive particles with a higher fracture strength than the workpiece, and the tool with higher fracture strength than abrasive particles





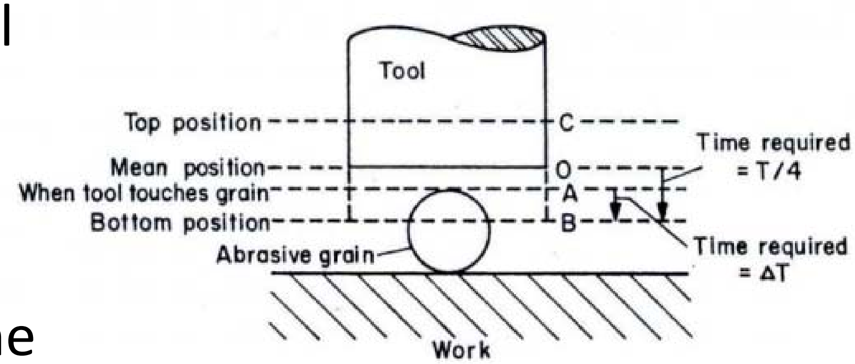
Mechanics of Cutting

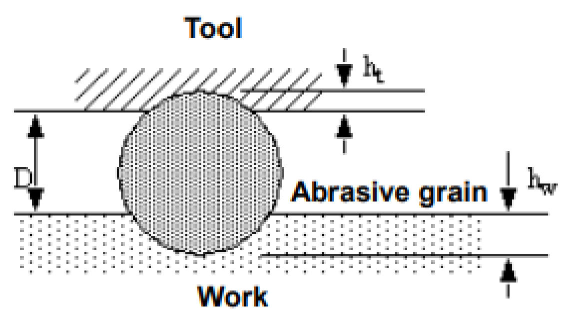
- Mechanical abrasion by localized direct hammering of the abrasive grains stuck between the vibrating tool and adjacent work surface.
- The microchipping by free impacts of particles that fly across the machining gap and strike the workpiece at random locations.
- The work surface erosion by cavitation in the slurry stream. 5% contribution in material removal
- Chemical corrosion due to slurry media



Mechanics of Cutting

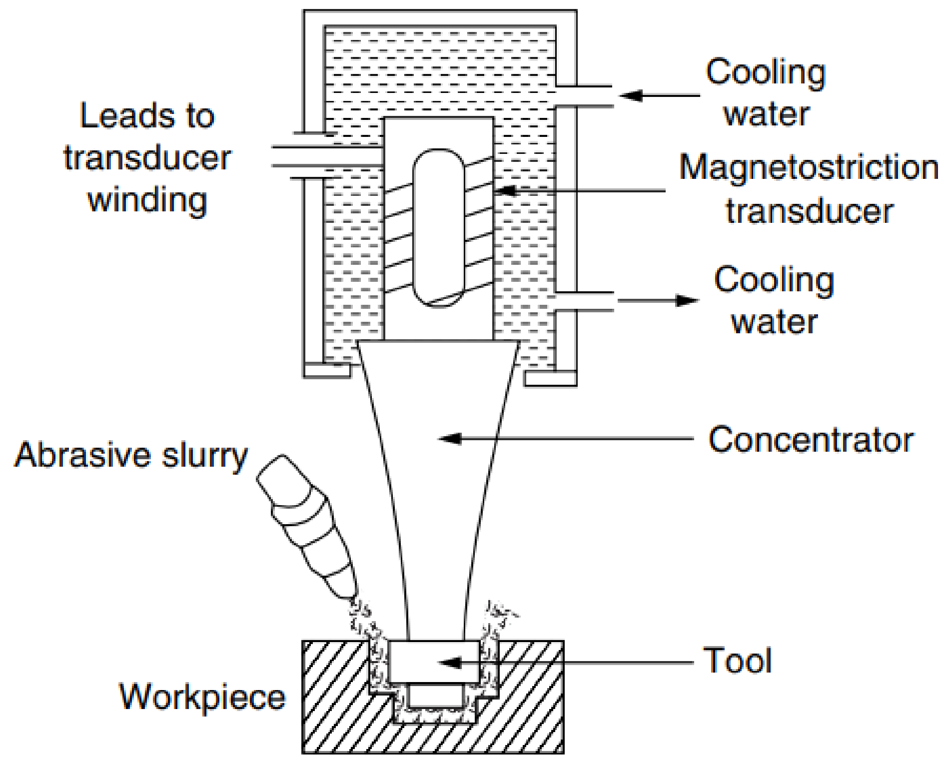
- The position A indicates the instant the tool face touches the abrasive grain.
- The period of movement from A to B represents the impact.
- The indentations, caused by the grain on the tool and the work surface at the extreme bottom position of the tool from the position A to position B is h (the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





Main Components of USM

- Ultrasonic Oscillator or Generator
- Transducer
- Tool holder
- Tool
- Abrasive slurry

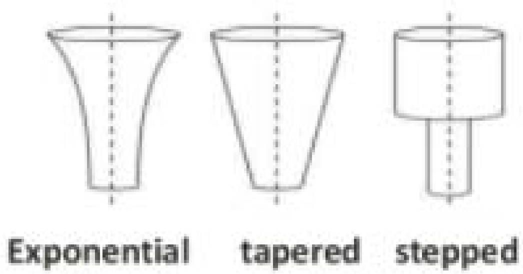


Components: Power supply and Transducer

- Ultrasonic Oscillator or Generator:
  - Converts electrical energy from low frequency to high frequency
- Transducer:
  - Convert electrical energy to mechanical energy
  - High frequency and low amplitude vibration
  - Two types: piezoelectric or magneto-strictive type
  - Piezoelectric crystals such as Quartz, barium titanate generate a small electric current when they are compressed and expands
  - Magneto-strictive transducer also changes its length when subjected to a strong magnetic field. These transducers are made of nickel, or nickel alloy sheets.

Components: Tool and Tool Holder

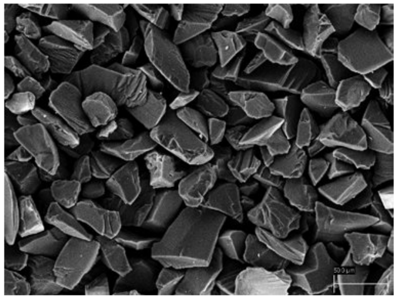
- Tool holder:
  - holds and connects the tool to the transducer.
  - Transmits the energy and, in some cases, amplifies the amplitude of vibration
  - The materials for toolholders are Monel, titanium, and stainless steel.
  - Good acoustic properties and high fatigue strength.
  - Should avoid welding between holder and transducer



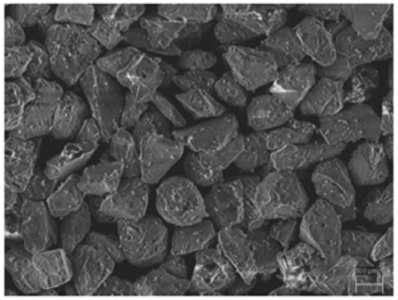
- Tool:
  - Must have high wear resistance and fatigue strength.
  - Usually made of relatively ductile materials (brass, stainless steel, mild steel, etc) so that the tool wear rate can be minimized.

Components: Abrasive Slurry

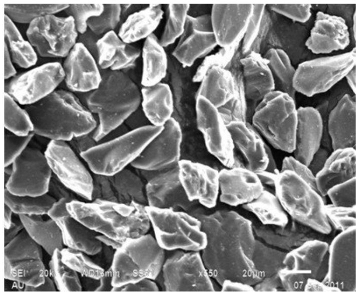
- A mixture of fine abrasive grains and water. The abrasive slurry is circulated between the oscillating tool and workpiece.
- Abrasive grains: boron carbide (B_4C), aluminum oxide (Al_2O_3), silicon carbide (SiC)
- Abrasive Particles have random sharp edges



Silicon Carbide



Aluminum Oxide



Boron Carbide

Components: Abrasive Slurry

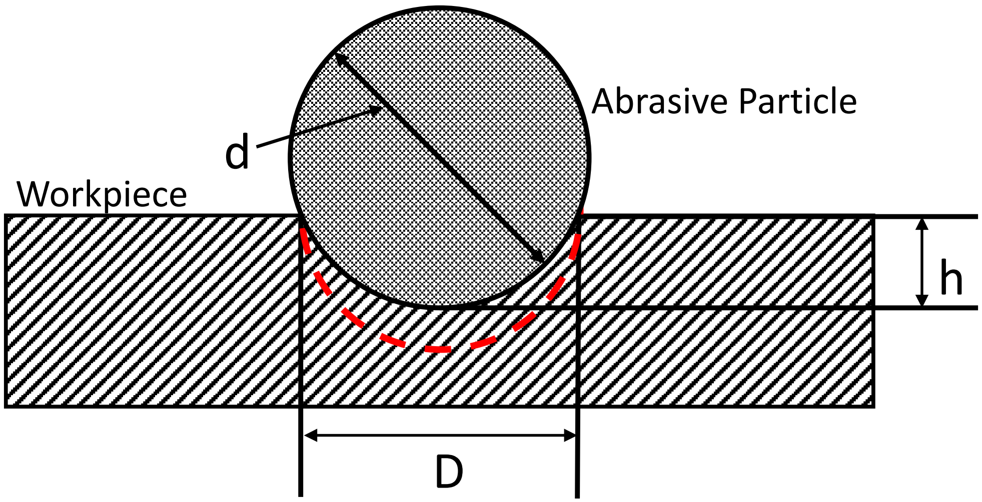
- B_4C is the best and most efficient among the rest but it is expensive.
- SiC is used on glass, germanium and most ceramics.
- Diamond dust is used only for cutting Diamond and Rubies.
- Water is the most commonly used fluid although other liquids such as Benzene, Glycerol and oils are also used

Assumptions

- Abrasive particles as spherical in shape
- Abrasive particles are rigid and hard
- All abrasive particles are similar
- All impacts are identical
- Material removal due to cavitation and chemical erosion are ignored
- Material removed in hemispherical shape per impact
- MRR is proportional to frequency and number of abrasive particles making impact and volume removed by particle per cycle

$$MRR \propto N\, V_p F$$

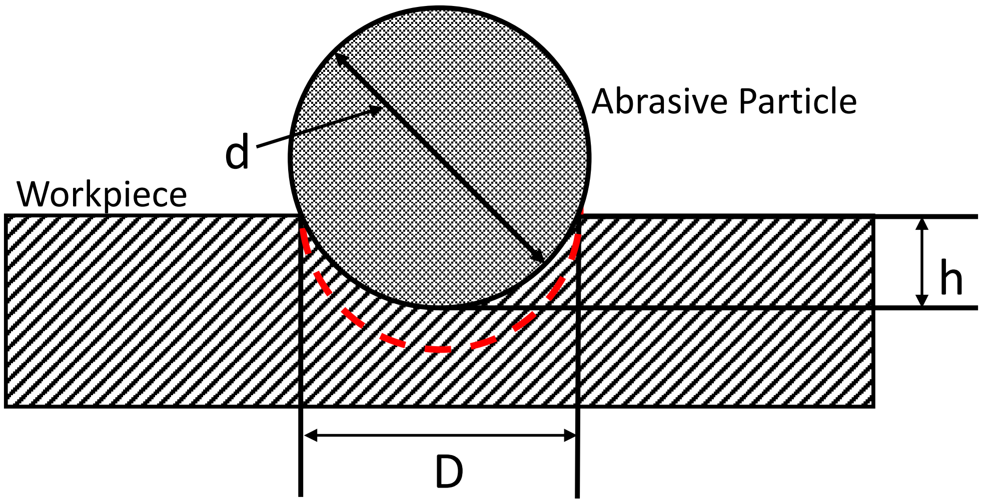
Volume of Material Removed/Particle

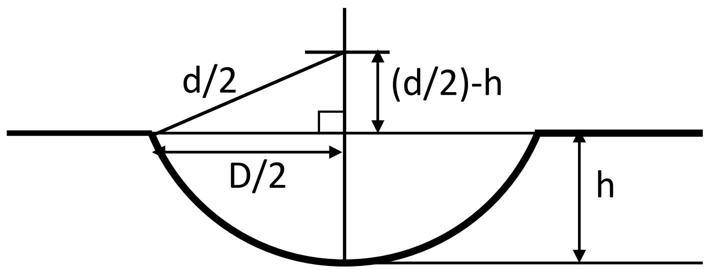


Volume removed /particle V_p

Total volume removed per cycle V

Volume of Material Removed/Particle





$$\left(\frac{d}{2}\right)^2 = \left(\frac{d}{2} - h\right)^2 + \left(\frac{D}{2}\right)^2 \longrightarrow D \approx 2\sqrt{dh}$$

Volume removed /particle $V_p = \frac{1}{2}\left(\frac{4\pi}{3}\left(\frac{D}{2}\right)^3\right) \longrightarrow V_p = \frac{2\pi}{3}(dh)^{3/2}$

Total volume removed per cycle $V = N\,V_p$

N=number of active abrasive particles

Estimation of Number of Active Abrasive Particles

- Concentration of abrasive particles = c   (volume by volume fraction)
- Cross section of the tool = A
- Total volume under the tool = V_s
- Total abrasive volume = $c \times V_s$
- Assume there is monolayer of abrasive particles then

  Volume of single layer of abrasives = $c \times A \times d$

- Volume of single abrasive = $\frac{4\pi}{3}\left(\frac{d}{2}\right)^3$
- Number of Active Abrasive Particles per cycle

$$N = \frac{c\,A\,d}{\frac{4\pi}{3}\left(\frac{d}{2}\right)^3} = \frac{6\,c\,A}{\pi d^2}$$

Material Removal Rate (MRR)

- Material removal rate , $MRR = \eta\ N\ V_p F$

where V_p = volume removed by a single abrasive particle

F = frequency of operation

N = number of particles impacting per cycle

η = constant (depend on diff parameters)

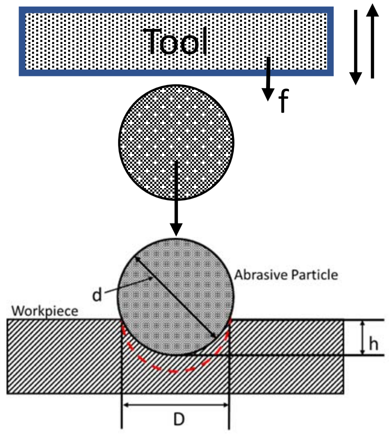
$$V_p = \frac{2\pi}{3}(dh)^{3/2} \text{ and } N = \frac{6\,c\,A}{\pi d^2}$$

$$MRR = \eta\ F\left(\frac{2\pi}{3}(dh)^{3/2}\right)\left(\frac{6\,c\,A}{\pi d^2}\right) = 4\,\eta\ F\ c\ A\sqrt{\left(\frac{h^3}{d}\right)}$$

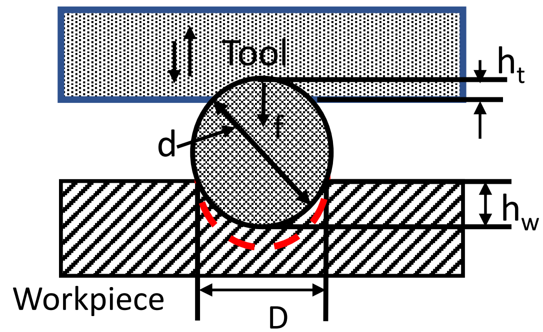
(h is unknown)

Estimation of Depth of Penetration

- Models proposed by Shaw (1965)
- There are two possibilities when the tool hits an abrasive particle.
- **Particle Throwing Model:** When the size of the particle is small and the gap between the bottom of the tool and work surface is large enough
- **Particle Hammering Model:** When size of particle is large and gap between the bottom of the tool and work surface is



Particle Throwing Model



Particle Hammering Model

In the both cases, a particle after hitting the work surface generates a crater of depth 'h' and radius 'D/2'.

Particle Throwing Model

- Displacement (Y) of the tool

$$Y = a\sin(2\pi F t)$$

- Velocity of the tool

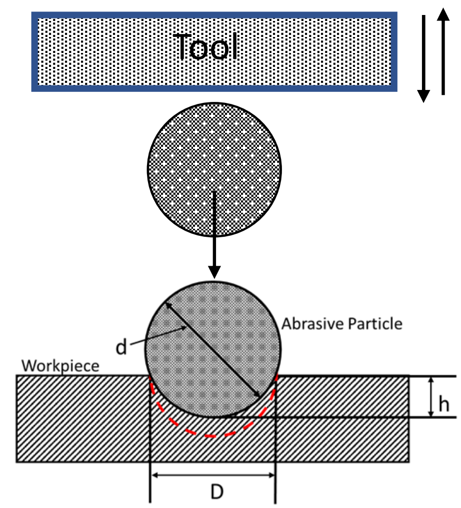
$$\frac{dY}{dt} = 2\pi a F \cos(2\pi F t)$$

- The maximum velocity of the tool

$$\left(\frac{dY}{dt}\right)_{max} = 2\pi a F$$

- The Kinetic Energy

$$KE = \frac{1}{2}\,\mathrm{m}\,(2\pi a F)^2$$



a is amplitude

F is frequency

Particle Throwing Model

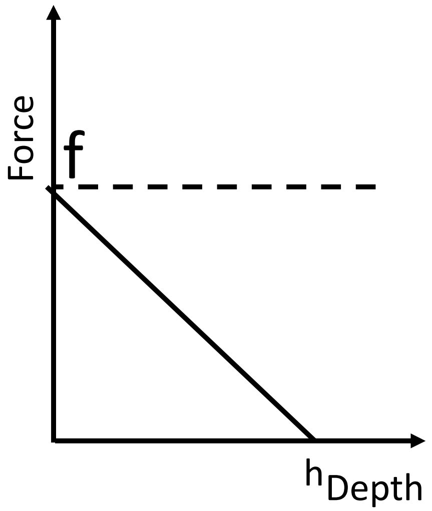
- The Kinetic Energy

$$KE = \frac{1}{2}\,\mathrm{m}(2\pi aF)^2$$

$$KE = \frac{1}{2}\left(\frac{4\pi}{3}\left(\frac{d}{2}\right)^3 \rho_p\right)(2\pi aF)^2$$

- An abrasive particle penetrates to the depth equal to ‘h’ into the workpiece. Then the work done by a particle is given by

$$W_p = \frac{1}{2}\,fh$$



Particle Throwing Model

- Kinetic Energy = Work Done

$$\frac{1}{2}\,fh = \frac{1}{2}\left(\frac{4\pi}{3}\left(\frac{D}{2}\right)^3 \rho_p\right)(2\pi aF)^2$$

- Depth of penetration

$$h = \frac{2\pi^3 a^2 F^2 D^3 \rho_p}{3f}$$

- Force in terms of mean stress of workpiece (σ_w)

$$f = \sigma_w A_w = \sigma_w \pi h d$$

Particle Throwing Model

- Depth of penetration

$$h = \frac{2\pi^3 a^2 F^2 d^3 \rho_p}{3\sigma_w \pi h d}$$

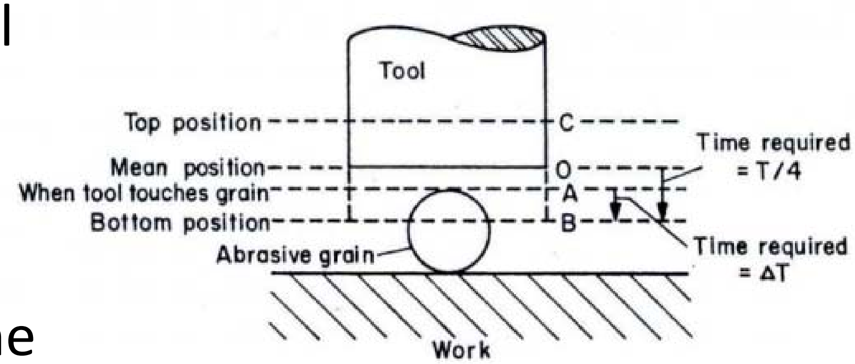
$$h = \pi a F d \sqrt{\frac{2\rho_p}{3\sigma_w}}$$

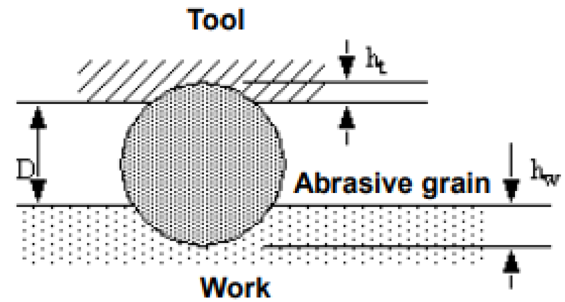
- Material Removal Rate:

$$MRR = 4\,\eta\,c\,A\,d\left(\frac{2\pi^2 a^2 \rho_p}{3\sigma_w}\right)^{3/4} F^{5/2}$$

Particle Hammering Model

- The position A indicates the instant the tool face touches the abrasive grain.
- The period of movement from A to B represents the impact.
- The indentations, 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 h (the total indentation).





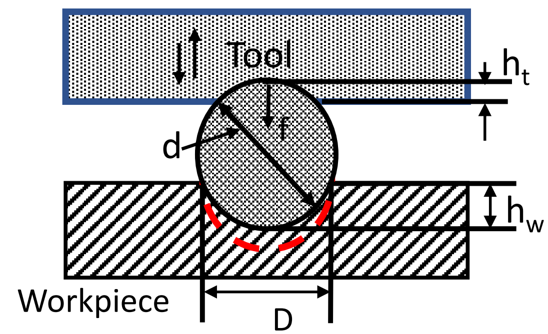
Particle Hammering Model

- Force f acting on particle for a short time ΔT during cycle time T
- Mean Force on the particle $f_{mean} = \frac{1}{T}\int_0^T f(t)dt$

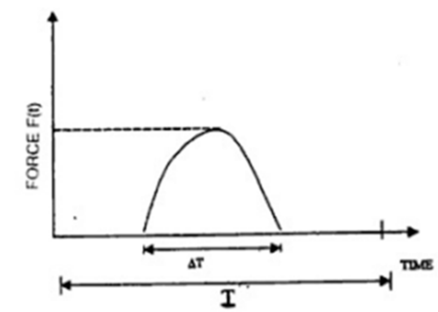
$$\int_0^t f(t)dt \approx \left(\frac{f}{2}\right)\Delta T$$

- Total Penetration due to hammering

$$h_h = h_t + h_w$$



a is amplitude
F is frequency

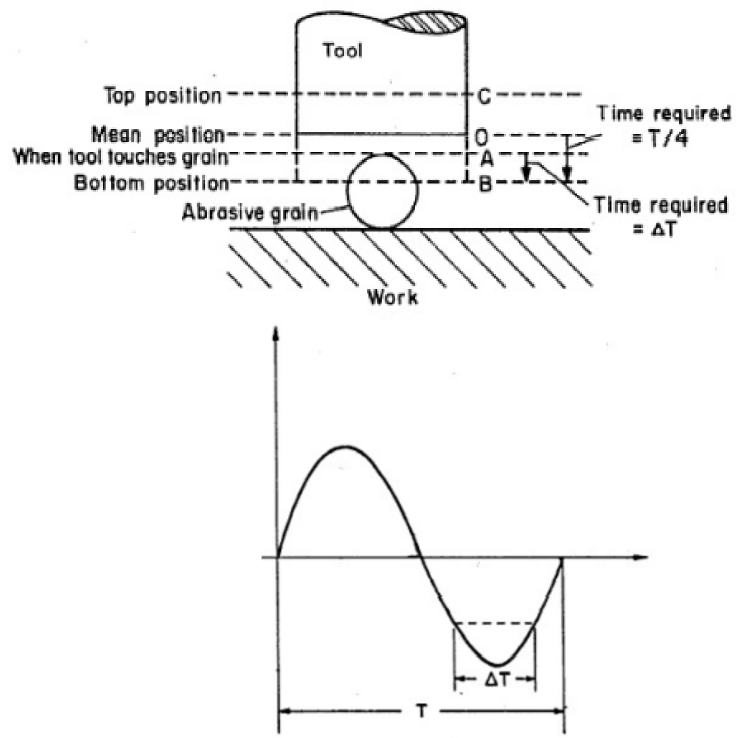


Particle Hammering Model

- The mean velocity of the tool during the quarter cycle (from O to B) = $\frac{a}{(T/4)}$
- Time (ΔT) required to travel from A to B:

$$\Delta T = \frac{h_h}{a}\left(\frac{T}{4}\right)$$

$$f = f_{mean}\left(\frac{8a}{h_h}\right)$$



Particle Hammering Model

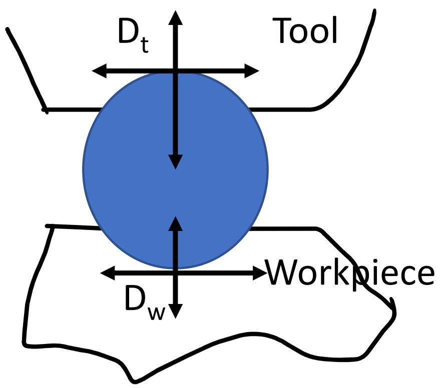
- Let 'N ' be the number of abrasive particles under the tool
- Stress acting on the tool (σ_t) and the workpiece (σ_w):

$$\sigma_w = f/N(\pi h_w d)$$

$$\sigma_t = f/N(\pi h_t d)$$

$$\sigma_t = \sigma_w \, (h_w/h_t)$$

$$\sigma_w = \frac{f_{mean}\left(\frac{8a}{h_h}\right)}{\left(\frac{6\,c\,A}{\pi d^2}\right)\,(\pi h_w d)} = \frac{8 f_{mean} a d}{6cA(h_w)^2\left(1+\left(\frac{h_t}{h_w}\right)\right)}$$



Particle Hammering Model

$$\frac{h_t}{h_w} = \frac{\sigma_w}{\sigma_t}$$

$$h_w = \sqrt{\frac{8 f_{mean} a d}{6 c A \sigma_w \left(1 + \left(\frac{\sigma_w}{\sigma_t}\right)\right)}}$$

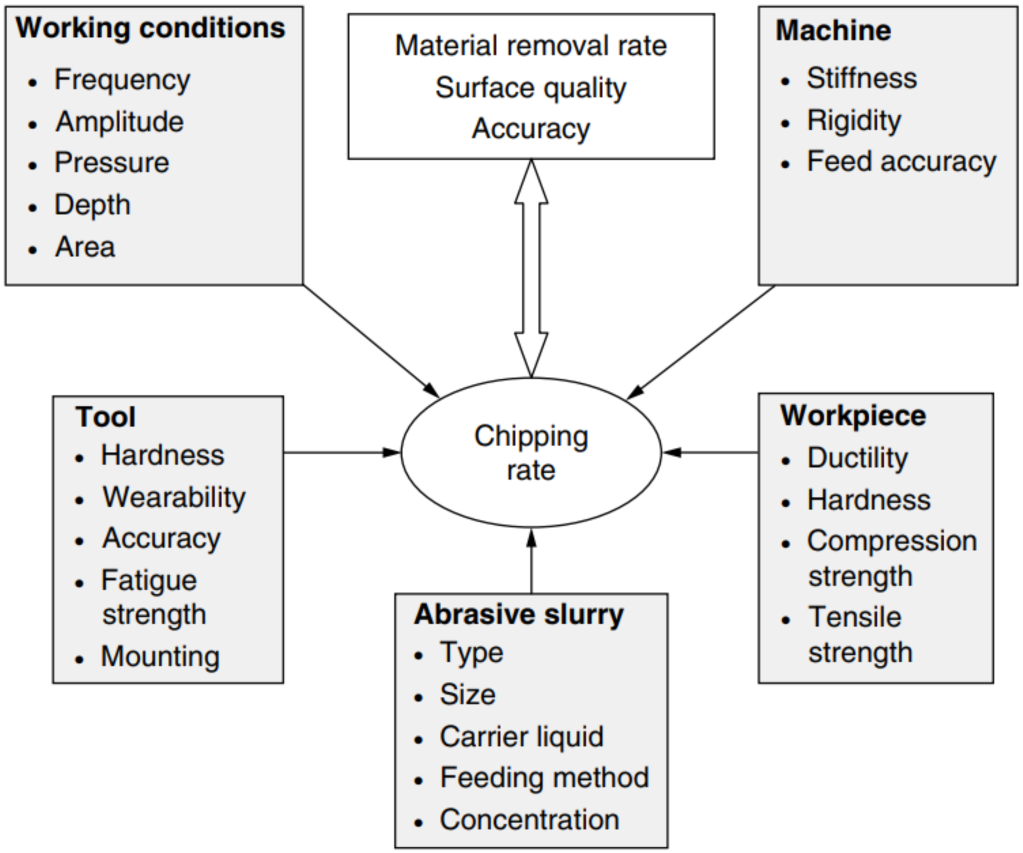
Material Removal Rate:

$$MRR = 4\,\eta\; c\; A\; dF \left(\frac{8 f_{mean} a}{6 c A d \sigma_w \left(1 + \left(\frac{\sigma_w}{\sigma_t}\right)\right)}\right)^{3/4}$$

Example

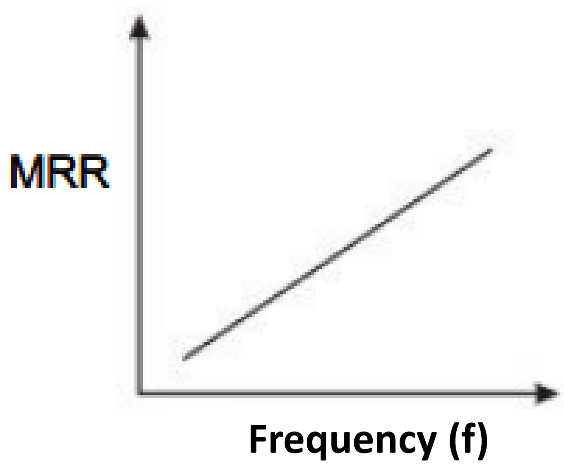
- Find out the approximate time required to machine a through hole of diameter equal to 6.0 mm in a tungsten carbide plate (Flow strength of work material = $6.9 \times 10^9 N/m^2$) of thickness equal to one and half times of hole diameter. The mean abrasive particle size is 0.015mm in diameter and having density of $3.8 \times 10^3 kg/m^3$. The feed force is equal to 3.5 N. The amplitude of tool oscillations is 25 microns and the frequency is equal to 25 kHz. The tool material is copper having flow strength= $1.5 \times 10^9 N/m^2$. The slurry contains one part of abrasives to one part of water. Parameter η=0.005.

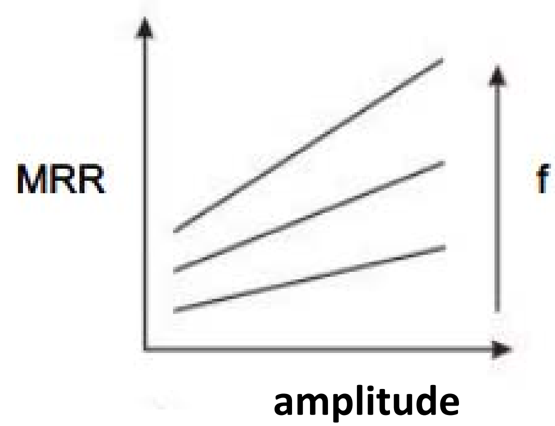
Factors affecting the USM



Effect of Frequency and Amplitude

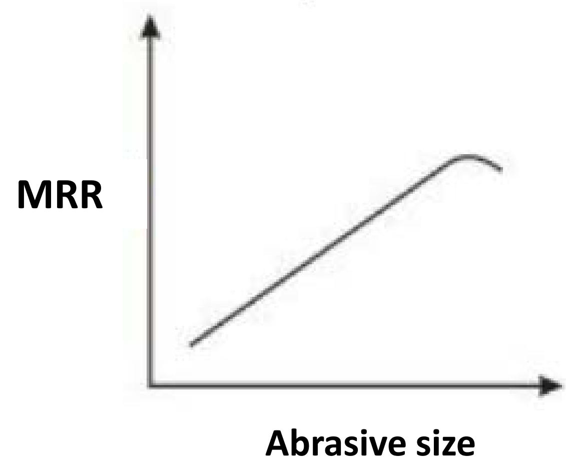
- With an increase in frequency of the tool head the MRR should increase proportionally. However, there is a slight variation in the MRR with frequency.
- When the amplitude of the vibration increases the MRR is expected to increase.

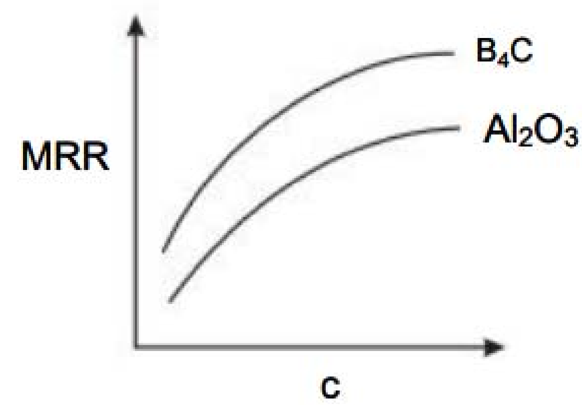




Effect of Abrasive Size and Concentration

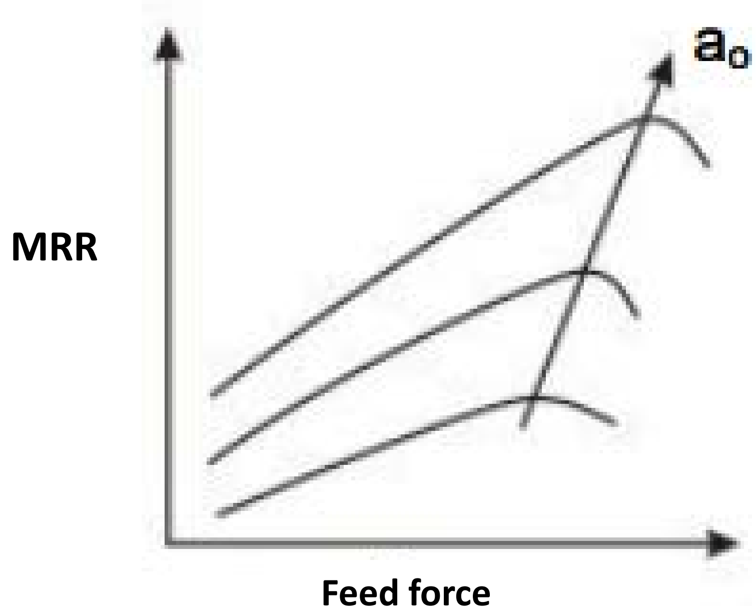
- MRR should also rise proportionately with the mean grain diameter d.
- When d becomes too large, the crushing tendency increases.
- Concentration of the abrasives directly controls the number of grains producing impact per cycle.
- MRR is proportional to $C^{1/4}$ so after C rises to 30% MRR increase is not very fast





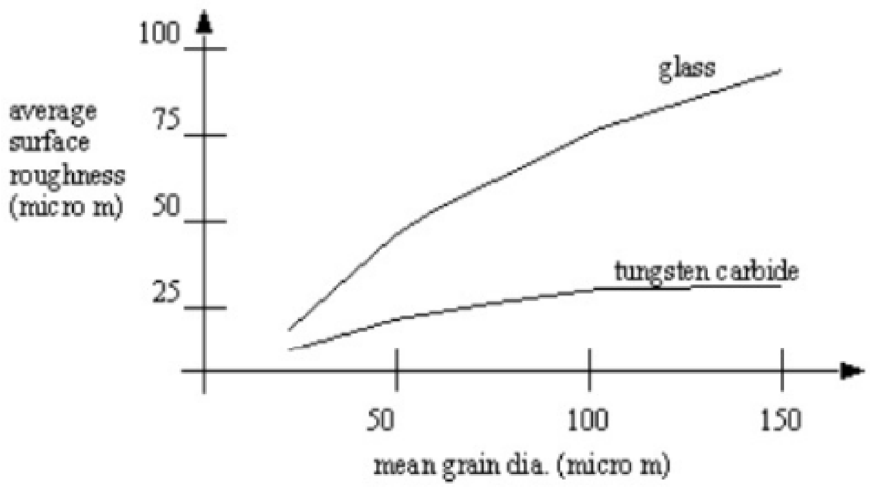
Effect of Feed Force

- MRR increases with increasing feed force but after a certain critical feed force it decreases because the abrasive grains get crushed under heavy load



Effect of Grain Size on Surface Finish

- The surface finish is more sensitive to grain size in case of glass which is softer than tungsten carbide.
- This is because in case of a harder material the size of the fragments dislodged through a brittle fracture does not depend much on the size of the impacting particles



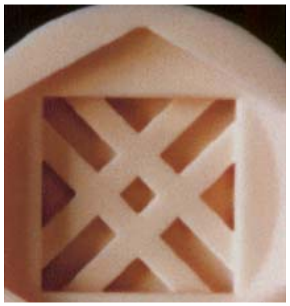
Advantages

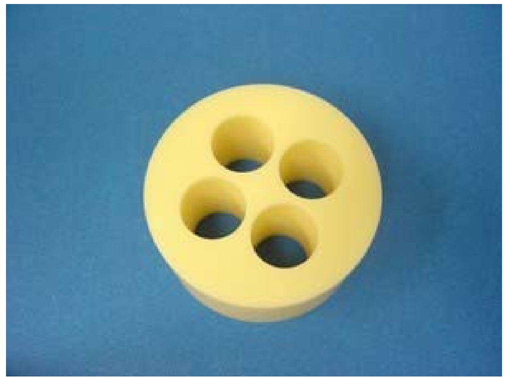
- Machining any materials irrespective of their conductivity
- Machining semi-conductor such as silicon, germanium etc.
- Suitable to precise machining of brittle materials.
- Can drill circular or non-circular holes in very hard materials
- Less stress because of its non-thermal characteristics
- USM does not produce electric, thermal, chemical damage.

Disadvantages

- Low material removal rate
- Rapid tool wears
- Machining area and depth limitation
- Not economical for soft materials

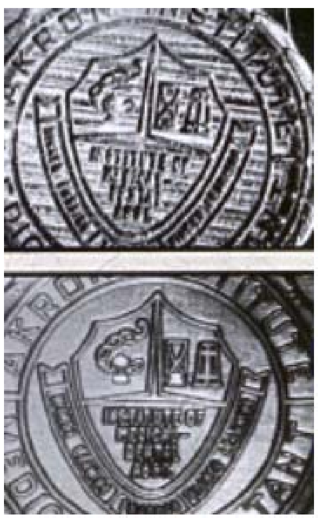
USM Parts

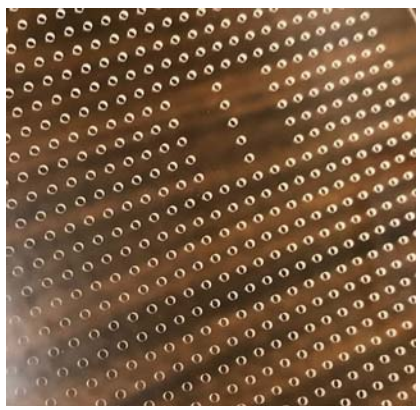




Ceramic holes (mmsonline.com)

Ceramics (bullentech.com)





Holes in Glass (swiftglass.com)

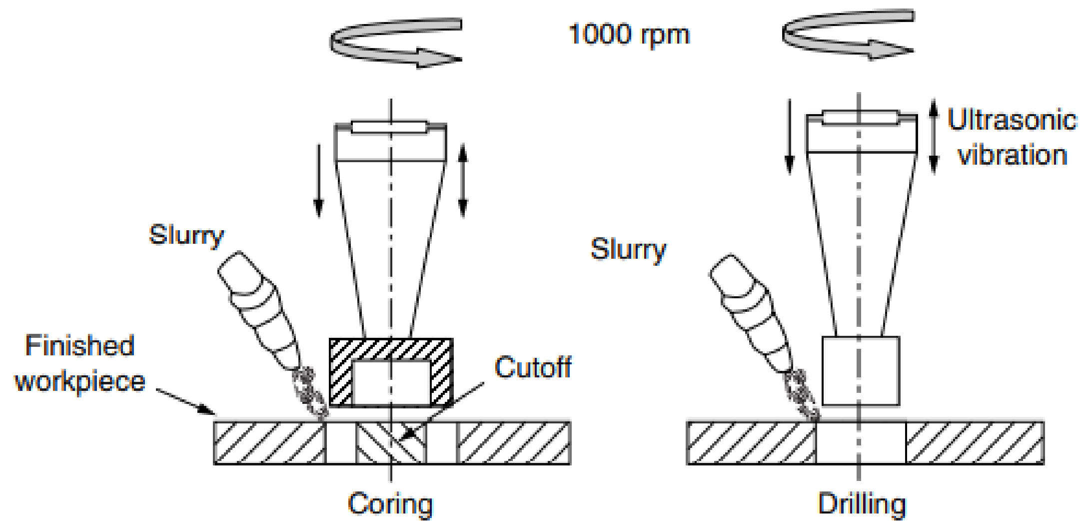
Graphite material

USM Hybrid Processes
Rotary Ultrasonic Machining (RUM)

- Rotating diamond plated tools in USM process
- Drilling, milling, grinding operations
- The combination of rotational motion and axial vibrations provides uniform tool wear, a high degree of hole roundness, and rapid removal of material from the cutting zone
- Machining of nonmetallic materials such as glass, alumina, ceramic, ferrite, quartz, zirconium oxide, ruby, sapphire, beryllium oxide, and some composite materials.

USM Hybrid Processes
Rotary Ultrasonic Machining (RUM)

- High removal rates, lower tool pressures for delicate parts, improved deep hole drilling, less breakout or through holes, and no core seizing during core drilling
- Longer tool life
- High accuracy and less overcut
- Rotary USM are expensive



Summary

Tool Vibration: **Amplitude** **Frequency**	 15-100 micron 15-30 kHz
Abrasive Material **Abrasive Size** **Abrasive Medium**	Al_2O_3, SiC, B_4C, Diamond dust, Boronsilicarbide 15-150 micron Water, Benzene, Glycerol and oils etc
Gap	25-40 micron
Tool Material	Mild Steel, Stainless steel, Brass (ductile and high wear resistance)
Work Material	Hardness> HRC 40 Carbide, Ceramics, Glass etc

References

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- Hassan El-Hofy, Advanced Machining Processes, McGraw-Hill Prof Med/Tech, 2005
- Helmi Youssef, Non-Traditional and Advanced Machining Technologies, CRC Press, 2020