TA 202A

Lecture 6

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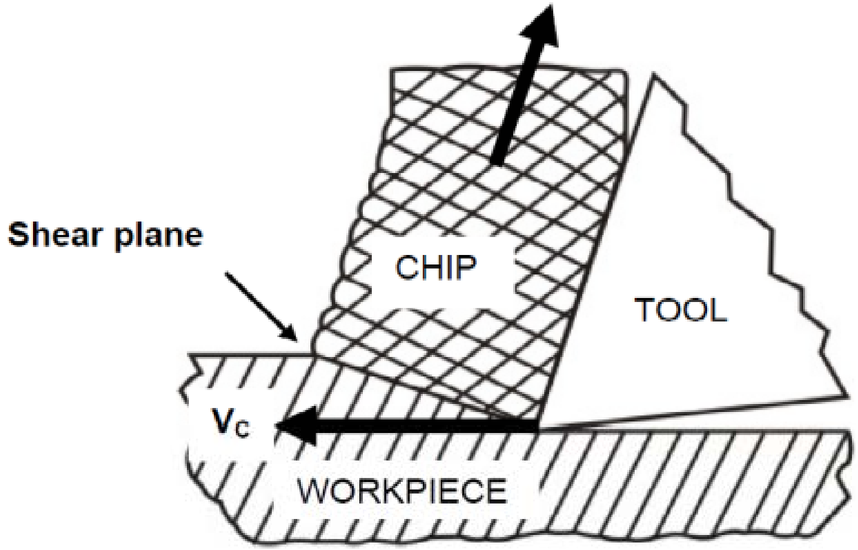
Conventional Process



Shear deformation in conventional machining leading to chip formation

Major characteristics of conventional machining

- Generally macroscopic chip formation by shear deformation
- Material removal takes place due to application of cutting forces – energy domain can be classified as mechanical
- Cutting tool is harder than work piece at room temperature as well as under machining conditions

Non-Conventional Machining Processes

Non-Traditional or Advanced

Engineering Materials

Metals and alloys

Plastics and composites

Ceramics

- Getting more popularity
- Definite advantages over others

How to machine them ?

Solution

Non-Conventional (Advanced) Machining Processes

Present Day Demand Trends in Industries

(Aerospace , Missiles , Automobiles, Nuclear Reactors, etc.)

For these one needs, Engineering Materials having much superior properties

- Very high temperature resistance
- Ultra high strength, hardness
- Difficult to machine by conventional machining methods

Work piece material hardness >> Tool material hardness

How to solve the problem ?

Non-Conventional (Advanced) Machining Processes

Workpiece hardness does not matter in non-conventional (Advanced) Machining Processes

Non-Conventional Processes Defined

A group of processes that remove excess material by various techniques involving mechanical, thermal, electrical, or chemical energy (or combinations of these energies) but do not use a sharp cutting tool in the conventional sense

Developed since World War II in response to new and unusual machining requirements that could not be satisfied by conventional methods

Need of Non-conventional (Advanced) Machining Processes ?

- Limitations of conventional machining methods (Workpiece Hardness, Surface Roughness, 3D Parts, Complex Geometries)

- Increased workpiece hardness → decreased economic cutting speed → lower productivity

- Rapid improvements in the properties of materials (Workpiece → Hardness, Strength etc.)

- Metals & Non – Metals : Stainless Steel, High strength and temperature resistant superalloys, etc.

- Tool material hardness **>>** Workpiece hardness

- Requires much superior quality of tool materials

Need of Non-conventional (Advanced) Machining Processes ?

- High production rate while processing difficult to machine materials
- Low cost of production
- Precision and ultraprecision machining (nano-meter machining)

↓

Requires material removal in the form of atoms and/or molecules

↓

Non-Conventional (Advanced) Machining Processes

Need of Non-conventional (Advanced) Machining Processes ?

Some Examples

Fabrication

Building of machines, structures, or process equipment by cutting, shaping and assembling components made from raw materials.

Fabrication
(Ignoring meso and nano fabrication)

Meso / Macro fabrication

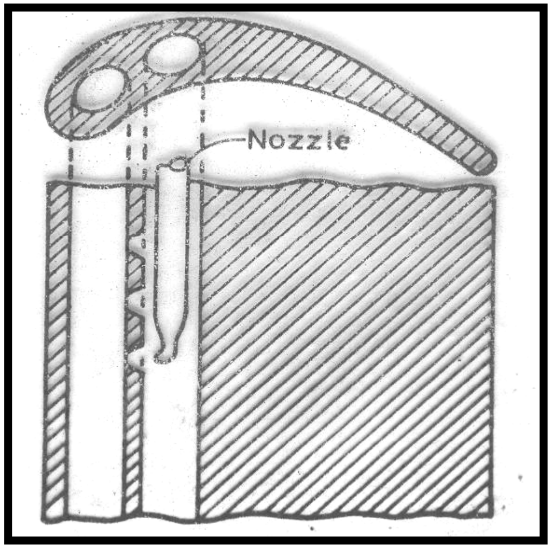
- Process of fabrication of structures that are measurable and observable
- Visible by naked eye
- Dimensions >= 1mm

Micro fabrication

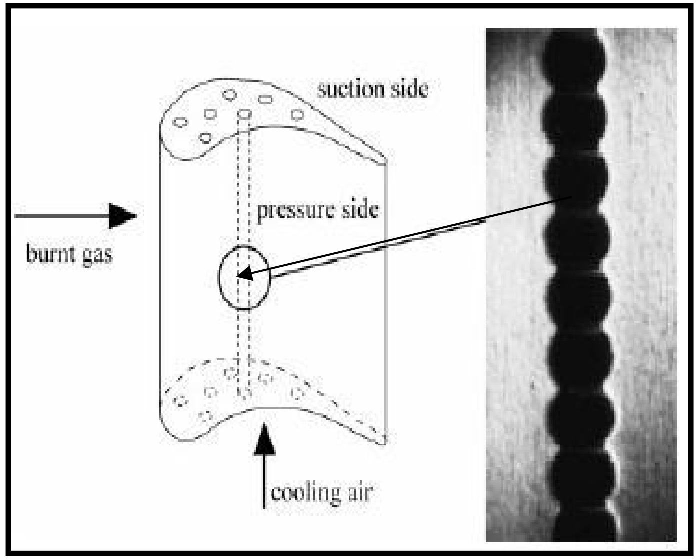
- Process of fabrication of miniature structures / features of µm sizes
- Needs microscopic equipments
- 999 nm <= Dimensions <= 999 µm

Machining of complex shaped workpieces

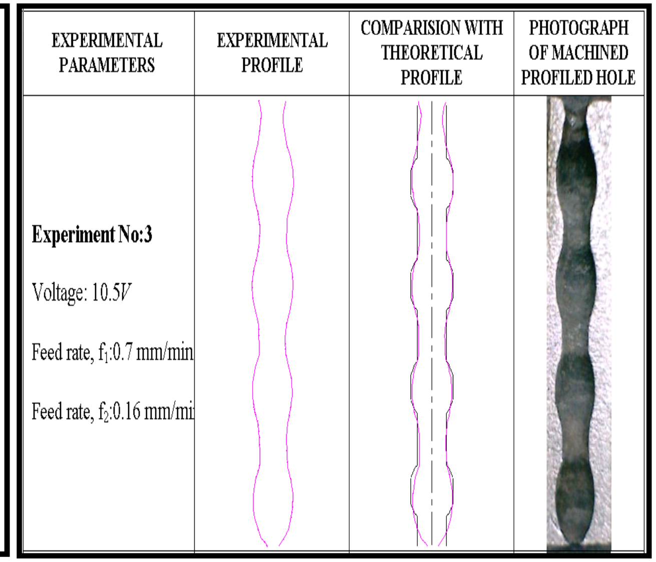
Electrochemical machining



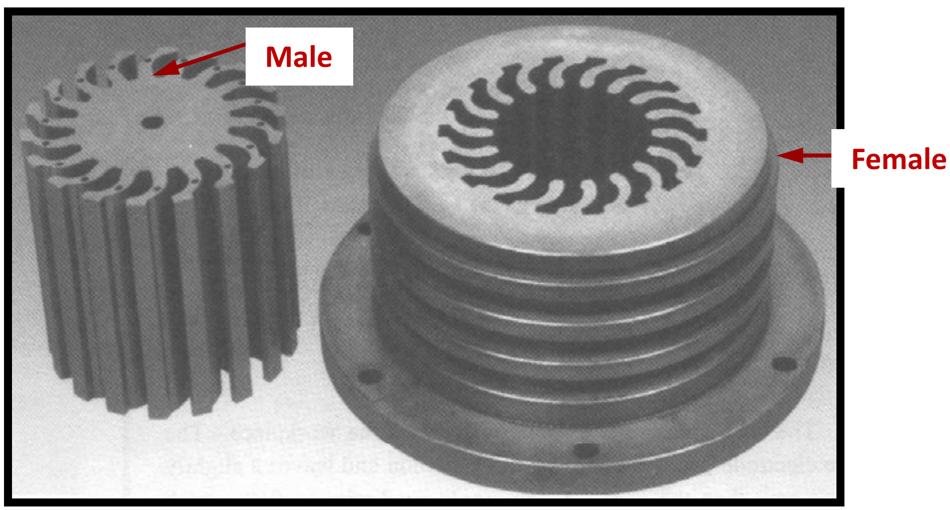
Hole normal to the wall



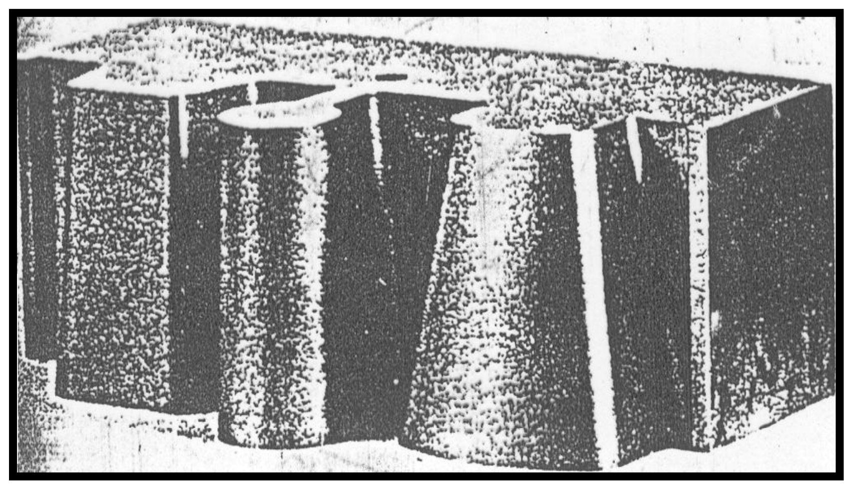
Turbine Blade with cooling Holes



Contoured Hole Drilled in Inconel Using ECM



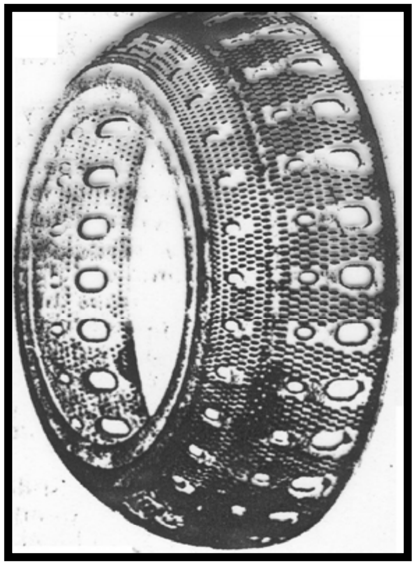
Precision wire EDM



Taper 3-d cutting using traveling wire - EDM

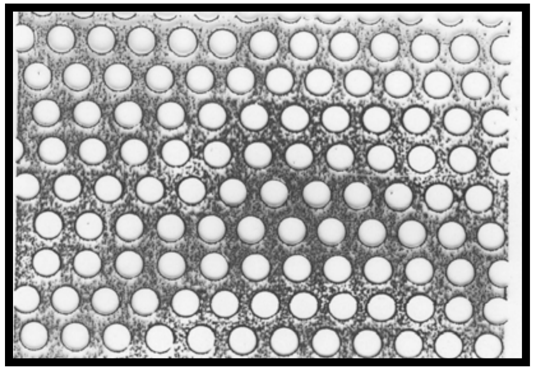
Pattern of holes drilled by EDM

Part of a helicopter turbine " holes drilled by EDM"



Hole ϕ= 0.09mm, Holes density = 4000/cm^2, workpiece - SS

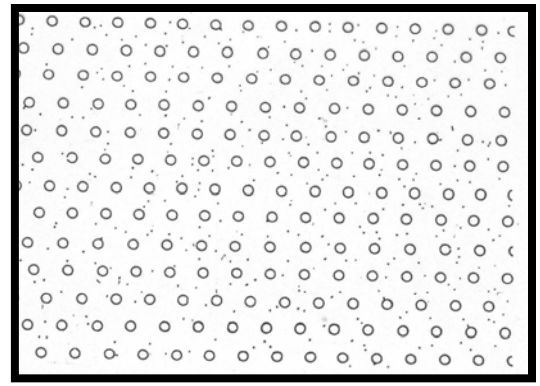
Thickness = 0.2 mm, Time = 10 μs/hole



Hole ϕ = 0.006mm (6 μm);

Holes density = 200,000/ cm^2

Thickness = 0.12 mm, time = 2μs / hole



Classification of Advanced Machining Processes

Classification is based on the kind of energy used : Mechanical, Thermoelectric, Electrochemical, chemical & biochemical.

Advanced Machining Processes

Mechanical

MACHINING

- Abrasive jet machining (AJM)
- Ultrasonic machining (USM)
- Water jet machining (WJM)
- Abrasive water jet machining (AWJM)

FINISHING

- Magnetic abrasive finishing (MAF)
- Abrasive flow finishing (AFM)
- Magnetorheological finishing (MRF)

Thermoelectric

- Plasma arc machining (PAM)
- Laser beam machining (LBM)
- Electron beam machining (EBM)
- Electric discharge machining (EDM)
- Ion beam machining (IBM)

Electrochemical & chemical

- Electrochemical machining (ECM)
- Chemical machining (CHM)
- Biochemical machining (BM)

Classification of Non-conventional Processes by Type of Energy Used

- Mechanical: erosion of work material by a high velocity stream of abrasives or fluid (or both) is the typical form of mechanical action
  - Water (WJC) and Abrasive Jet Machining
  - Ultrasonic Machining (UM)

- Electrical : electrochemical energy to remove material (reverse of electroplating)
  - Electrochemical Machining (ECM)
  - Electrochemical Grinding (ECG)

- Thermal : thermal energy usually applied to small portion of work surface, causing that portion to be removed by fusion and/or vaporization
  - Electric Discharge Process (EDM)
  - Electron Beam Machining (EBM)
  - Laser Beam Machining (LBM)

- Chemical : chemical etchants selectively remove material from portions of workpart, while other portions are protected by a mask
  - Chemical Machining (CHM)

Some Important Characteristics of Advanced Machining Processes & Machine Tools

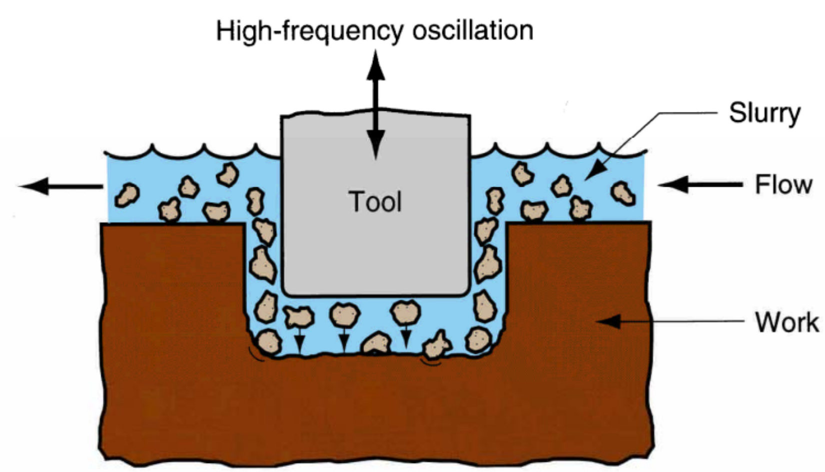
- Performance is independent of strength barrier
- Performance depends on thermal, electrical, magnetic and/or chemical properties of workpiece materials
- Material removal may occur with or without chip formation
- There may not be a physical tool present
- The tool need not be harder than the work piece material
- Use different kinds of energy in direct form
- In general, low MRR but better quality products
- Comparatively high initial investment cost of machine tools and high – operating cost

Mechanical Energy Processes

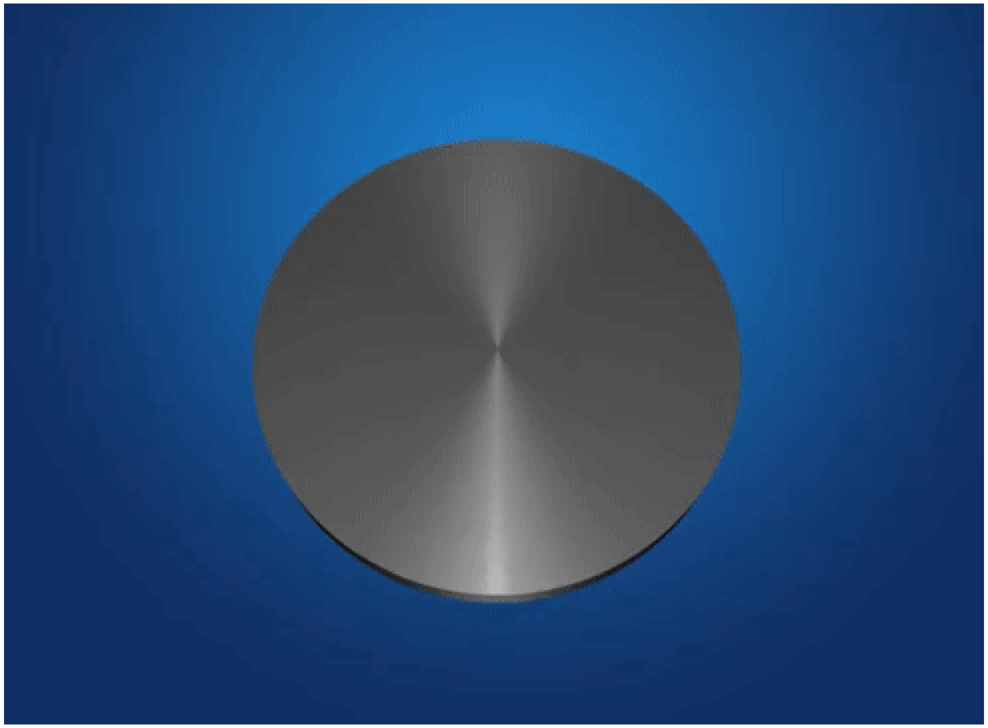
- Ultrasonic machining
- Water jet cutting
- Abrasive water jet cutting
- Abrasive jet machining

Ultrasonic Machining (USM)

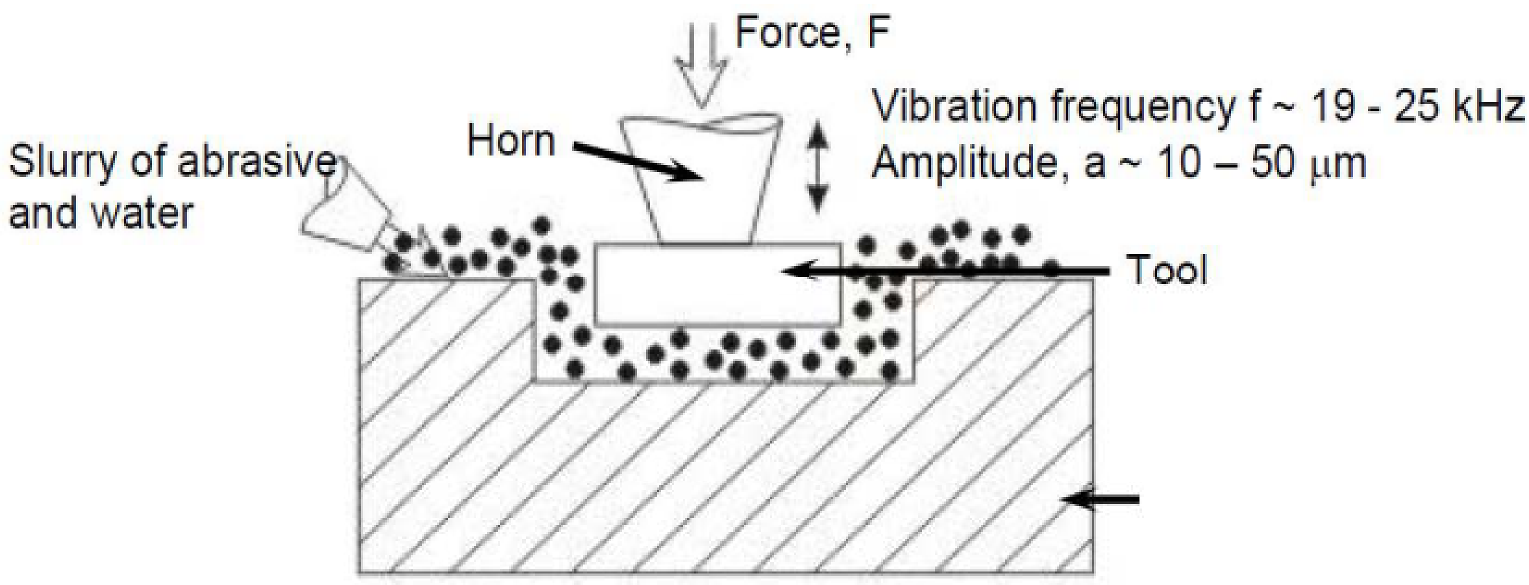
Abrasives contained in a slurry are driven at high velocity against work by a tool vibrating at low amplitude and high frequency



Ultrasonic machining



- Tool oscillation is perpendicular to work surface
- Tool is fed slowly into work
- Shape of tool is formed in part



Amplitude of vibration	:	10-50 μm
Frequency of vibration	:	19-25 KHz
Abrasive size	:	15-150 μm
Abrasive types	:	Al_2O_3 , SiC, B_4C, Diamond

- Grit size determines the surface finish on the new work surface.

- The removal rate in USM increases with increasing frequency and amplitude of vibration.

- The cutting action on the tool as well as the work. As the abrasive particles erode the work surface, they also erode the tool, thus affecting its shape.

- It is therefore important to know the relative volumes of work material and tool material removed during the process. 100:1 for cutting glass, 1:1 for cutting tool steel.

- The slurry in USM consists of a mixture of water and abrasive particles. Concentration of abrasives in water ranges from 20% to 60%. The slurry must be continuously circulated to bring fresh grains into action at the tool–work gap. It also washes away chips and worn grits created by the cutting process.

USM Applications

- Hard, brittle work materials such as ceramics, glass, and carbides (which are poor conductors of electricity and thus cannot be processed by ECM and EDM)
- Also successful on certain metals, such as stainless steel and titanium
- Shapes include non-round holes, holes along a curved axis
- “Coining operations”- pattern on tool is imparted to a flat work surface

Limitations

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

Mechanics of Material Removal

The reasons for material removal in an USM process are believed to be:

1. The hammering of the abrasive particles on the work surface by the tool.
2. The impact of free abrasive particles on the work surface.
3. The erosion due to cavitation.
4. The chemical action associated with the fluid used.

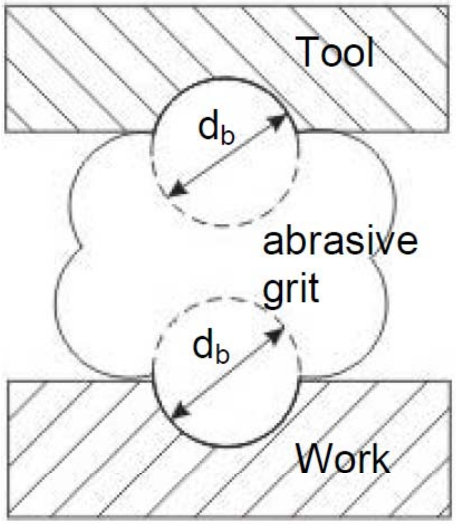
Many researchers have tried to develop the theories to predict the characteristics of ultrasonic machining. The model proposed by M.C. Shaw is generally well accepted and explains the material removal process well.

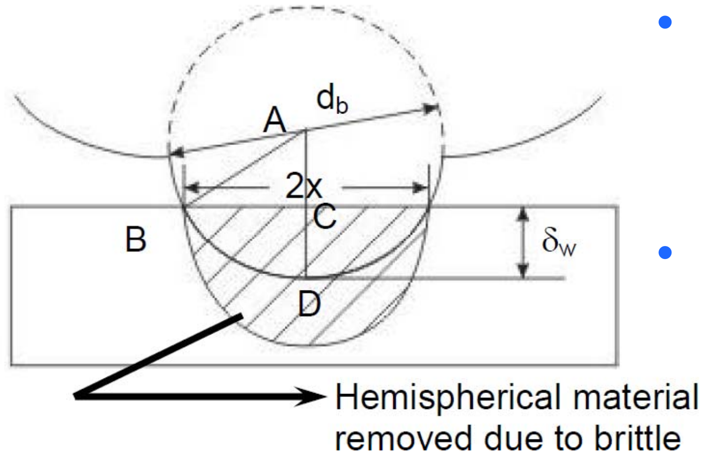
M.C. Shaw's Model of USM Mechanics

In this model the direct impact of the tool on the grains in contact with the work piece is taken into consideration. Also, the assumptions made are:

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

Mechanics of Material Removal





- Material removal primarily occurs due to the indentation of the hard abrasive grits on the brittle work material.
- Material is removed due to crack initiation, propagation and brittle fracture of the material.

Assumption: Material removal take place only due to impact of abrasives between tool and workpiece, followed by indentation and brittle fracture of the workpiece.

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

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

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

$x^2 = d_b\delta_w$ neglecting δ_w^2 as $\delta_w << d_b$

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

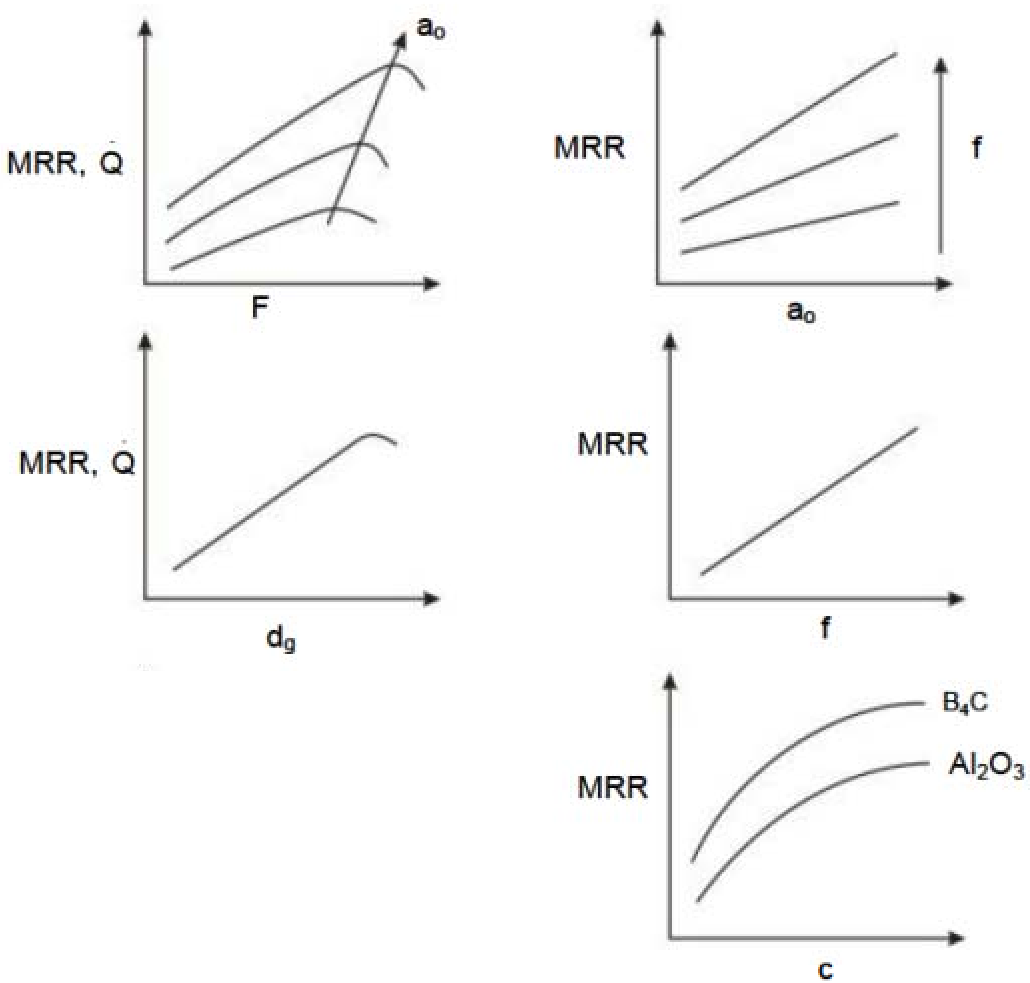
If at any moment of time, there are an average 'n' of grits and the tool is vibrating at a frequency 'f' then material removal rate can be expressed as

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

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

MRR_w = material removal rate
n = avg number of grits making impact per cycle
f = tool vibrating frequency
δ_w = indentation depth in the work material
d_b = abrasive grit size
Γ_w = Volume of work material removed per impact

Effect of Process Parameters



F	feed force
a_o	vibration amplitude
f	vibration frequency
d_g	grit size
c	grit material

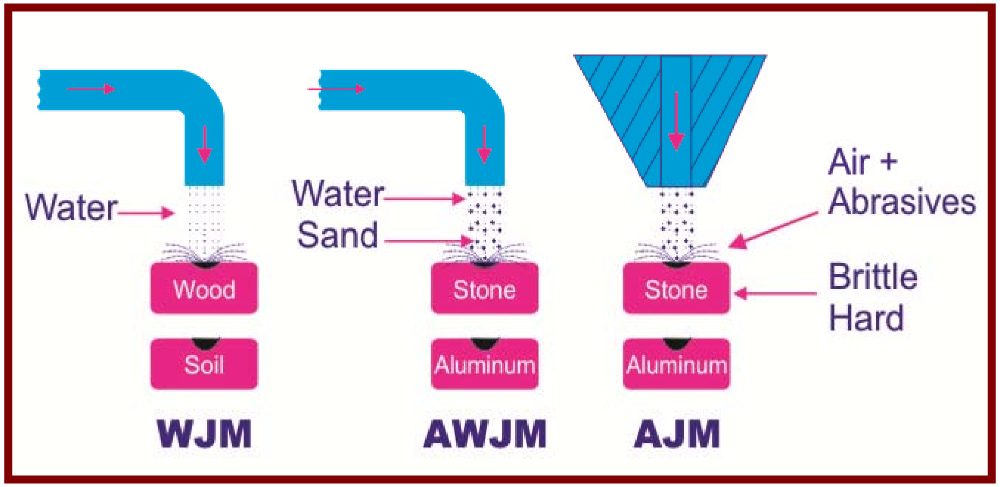
Summary

Mechanics of material removal	Brittle fracture caused by impact of abreasive grains due to tool vibrating at high frequency
Medium	Slurry
Abrasives	B_4C, SiC, Al_2O_3, diamond 100-800 grit size
Vibration Frequency Amplitude	 15-30 kHz 25-100 μm
Tool Material MRR/Tool wear rate	 Soft steel 1.5 for WC workpiece, 100 for glass workpiece
Gap	25-40 μm
Critical parameters	Frequency, amplitude, tool material, grit size, abrasive material, feed force, slurry concentration, slurry viscosity
Materials application	Metals and alloys (particularly hard and brittle), semiconductors, nonmetals, e.g., glass and ceramics
Shape application	Round and irregular holes, impressions
Limitations	Very low MRR, tool wear, depth of holes and cavities small

Can water cut metals ?

Yes. But how?

Water Jet Machining (WJM), Abrasive Water Jet Machining (AWJM), Abrasive Jet Machining (AJM)

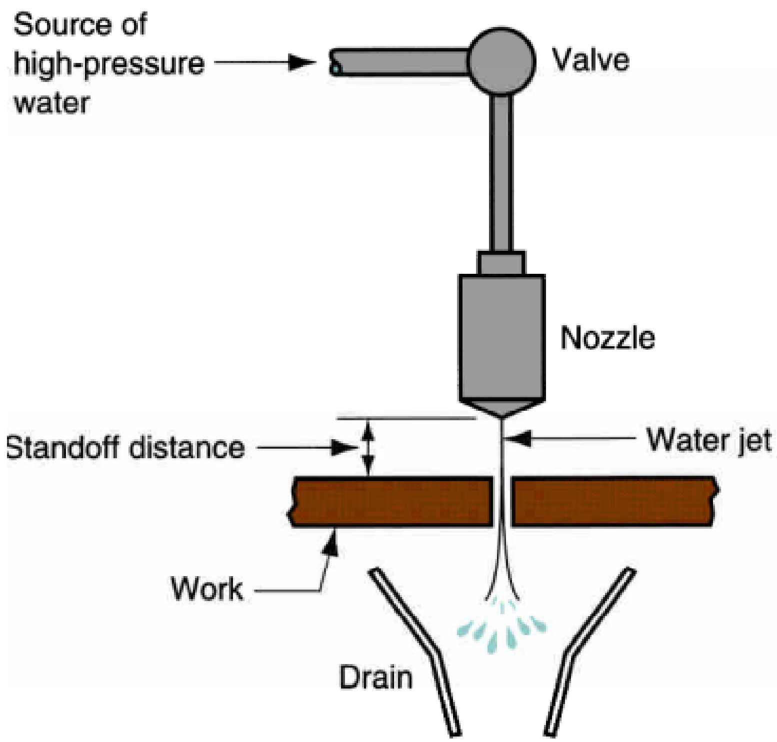


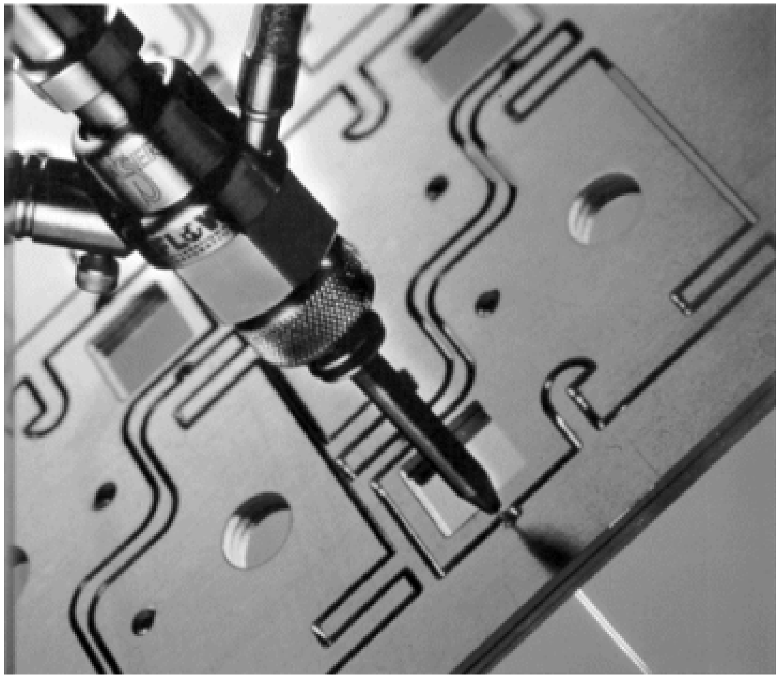
- K.E. of water and/or abrasive particles makes it happen.
- Velocity of the abrasive water jet → as high as 900 m/s.

Water jet machining

Abrasive water jet machining

Water Jet Machining (WJM)





A fine (0.1 – 0.4 mm dia.), high pressure (400 MPa), high velocity (900 m/s) stream of water is directed at the work surface to cause cutting

Important process parameters

- Standoff distance: small to avoid dispersion of the fluid stream (~ 2-3 mm)
- Nozzle opening diameter: affects precision
- Water pressure: high for thicker materials
- Cutting feed rate: The velocity at which the WJM nozzle is traversed along the cutting path

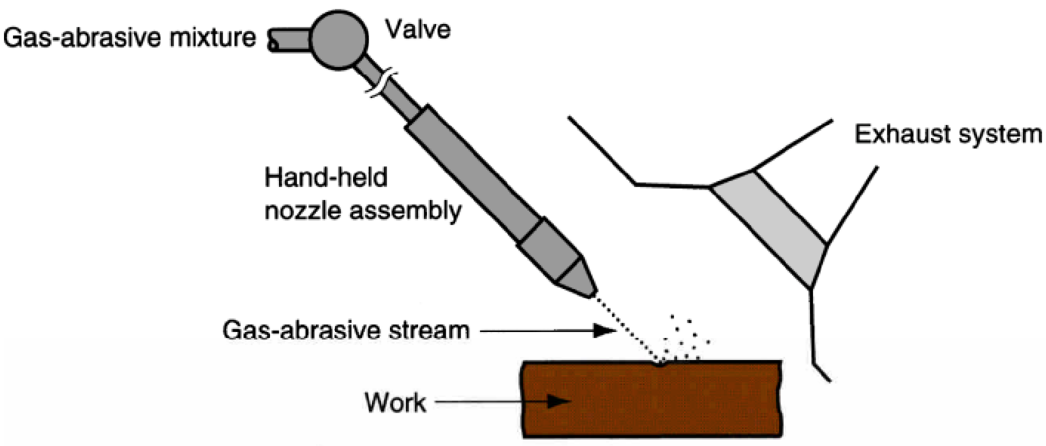
WJM Applications

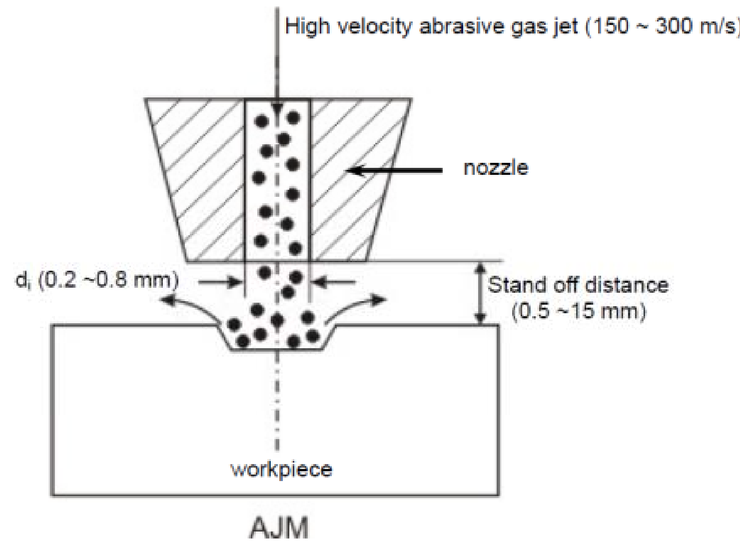
- Usually automated by CNC or industrial robots to manipulate nozzle along desired trajectory
- Used to cut narrow slits in flat stock, such as plastics, textiles, composites, floor tile, carpet, leather and cardboard
- Not suitable for brittle materials (e.g., glass)
- WJC advantages: no crushing or burning of work surface, minimum material loss, no environmental pollution, and ease of automation

Abrasive Water Jet Machining (AWJM)

- When WJM is used on metals, abrasive particles must be added to jet stream
- Additional process parameters: abrasive type, grit size, and flow rate
- Abrasives: aluminum oxide, silicon dioxide, and garnet (a silicate mineral)
- Grit sizes range between 60-120 μm
- Grits added to water stream at about 0.25 kg/min after it exits nozzle

Abrasive Jet Machining (AJM)



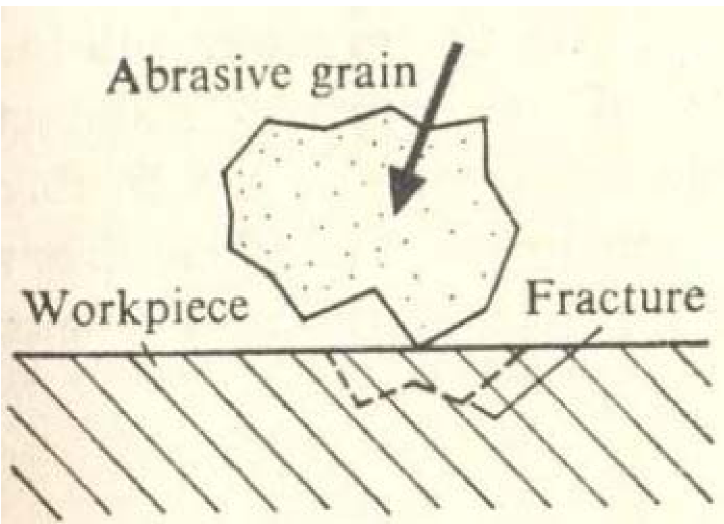


Abrasive impinges on work material with high velocity.

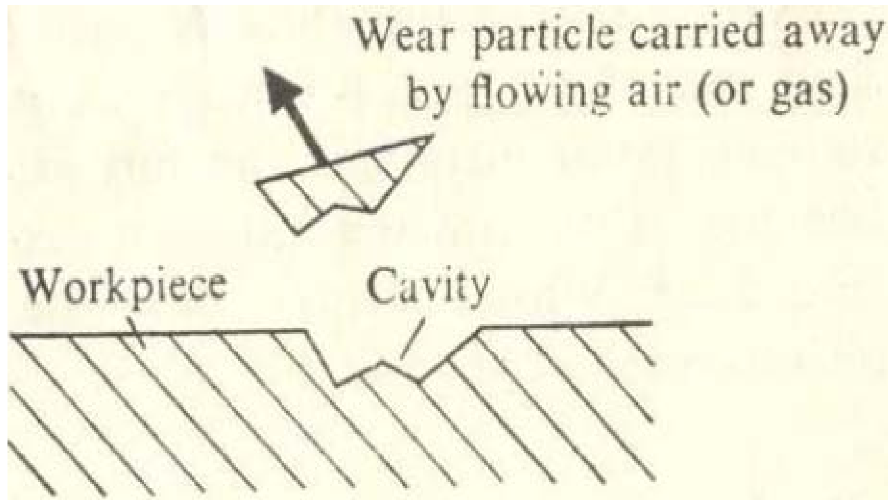
- Jet of abrasive is carried by gas
- High velocity stream of abrasive in gas – by conversion of pressure energy of carrier gas to its KE.
- SOD and impingement angle – setting parameter
- Velocity jet removes material by microcutting action and brittle fracture.
- AJM typical parameters are
  - SOD – 2 mm
  - Nozzle of ID – 0.5 mm
  - Velocity – 200 m/s

Mechanics of AJM

Abrasive particle impinges on the work surface at a high velocity and this impact causes a tiny brittle fracture and the following air or gas carries away the dislodged small work piece particle.



Fracture of work surface



Formation of cavity

The process is more suitable when the work material is brittle and fragile.

Mechanics of AJM

- The process is more suitable when the work material is brittle and fragile.
- A model for the material removal rate (MRR) is available from Sarkar and Pandey, 1980.

The MRR (Q) is given as

$$Q = \chi Z d^3 v^{3/2} \left(\frac{\rho}{12 H_w} \right)^{3/4}$$

$$\begin{aligned}
where\ Z &= No. of\ abrasive\ particles\ impacting\ per\ unit\ time \\
d &= Mean\ diameter\ of\ abrasive\ grains \\
v &= Velocity\ of\ abrasive\ grains \\
\rho &= Density\ of\ abrasive\ grains \\
H_w &= Hardness\ of\ the\ workpiece\ (flow\ stress) \\
\chi &= Constant
\end{aligned}$$

Process Parameters and Machining Characteristics

- **Abrasive material – Al_2O_3 / SiC / glass beads**
  - Shape – irregular / spherical
  - Size – 10 - 50 µm
  - Mass flow rate – 2 - 20 gm/min
- **Carrier gas**
  - Composition – Air, CO_2, N_2
  - Density – Air ~ 1.3 kg/m^3
  - Velocity – 500 - 700 m/s
  - Pressure – 2 - 10 bar
  - Flow rate – 5 - 30 lpm
- **Abrasive Jet**
  - Velocity – 100 - 300 m/s
  - Mixing ratio (M)– mass flow ratio of abrasive to gas
  - Stand-off distance – 0.5 - 5 mm
  - Impingement Angle – 60^0 - 90^0
- **Nozzle**
  - Material – WC / sapphire
  - Diameter – (Internal) 0.2 - 0.8 mm
  - Life – 10 - 300 hours

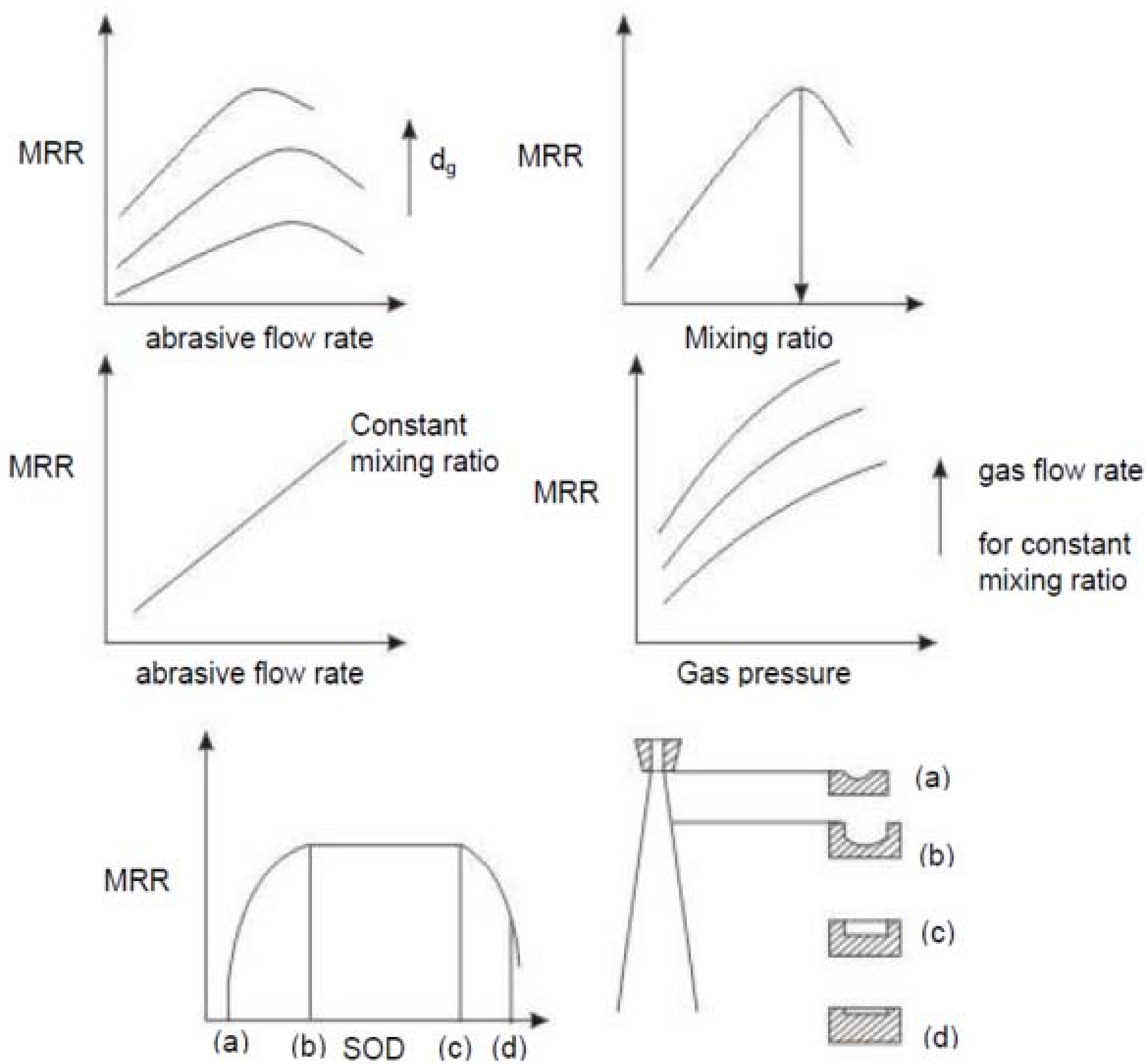
$$\text{Mass ratio}\,(\alpha) = \frac{\text{Abrasive mass flow rate}}{\text{Abrassive and carrier gas combined mass flow rate}}$$

$$\alpha = \frac{\dot{m}_a}{\dot{m}_{a+g}}$$

$$M = \frac{\text{Volume flow rate of abrasive particles}}{\text{Volume flow rate of carrier gas}} = \frac{\dot{V}_a}{\dot{V}_g}$$

$$M = \frac{\dot{V}_a}{\dot{V}_g}$$

Effect of Process Parameters MRR



Limitation and Advantages

Normally used as a finishing process rather than cutting process

Applications

- For drilling holes of intricate shapes in hard and brittle materials
- For machining fragile, brittle and heat sensitive materials
- AJM can be used for different jobs, such as drilling, cutting, deburring, cleaning and etching.
- Micro-machining of hard and brittle materials (thin flat stock) (e.g., glass, silicon, mica, ceramics)

Limitations

- MRR is rather low (around ~ 15 mm^3 /min for machining glass)
- Abrasive particles tend to get embedded particularly if the work material is ductile
- Tapering occurs due to flaring of the jet
- Environmental load is rather high

Recap of this Lecture

- Introduction to Non-Conventional Machining Processes
- Their Classification
- Mechanical Energy based Processes
  - Ultrasonic Machining Process
  - Water Abrasive Jet Machining
  - Abrasive Water Jet Machining
  - Abrasive Jet Machining

Next Lecture

Electrical Energy based Processes