ME338 – Manufacturing Process II
Lecture 12 : Abrasive Jet Machining (AJM)

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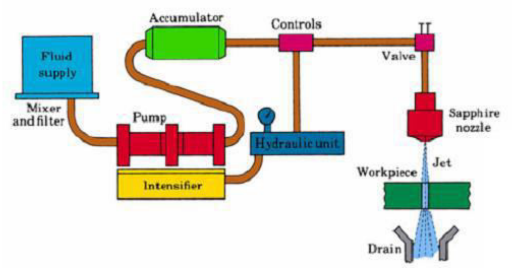
Abrasive jet machining

Abrasive Water Jet Machining

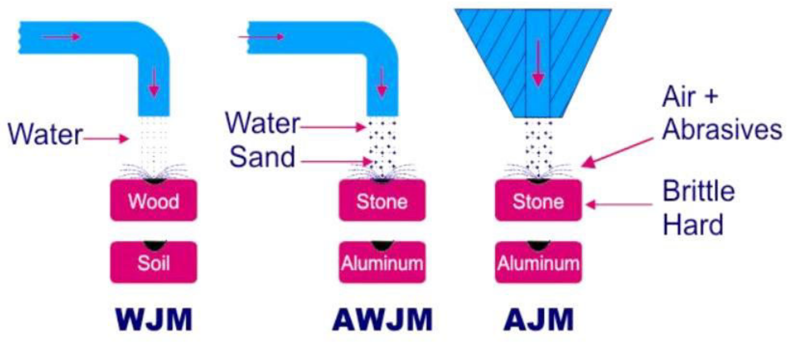
- Dr. Franz in 1950s: high pressure water cutting for forestry and wood cutting
- Dr. Mohamed Hashish in 1979: added abrasive particles to increase cutting force and ability to cut hard materials including steel, glass and concrete (AWJM)
- First commercial use was in automotive industry to cut glass in 1983
- Used in aerospace industry for cutting materials like composites like carbon fiber
- WJM is a form of microerosion. It works by forcing a large volume of water through a small orifice in the nozzle.
- The extreme pressure of the accelerated water particles contacts a small area of the workpiece and acts like a saw and cuts a narrow groove in the material.



Abrasive Water Jet Machining

- High pressure water (20,000-60,000 psi)
- Can cut extremely thick parts (5-10 inches possible)
  - Thickness achievable is a function of speed
  - Twice as thick will take more than twice as long
- Tight tolerances achievable
  - Current machines 0.002" (older machines much less capable ~ 0.010"
- Jet will lag machine position, so controls must plan for it

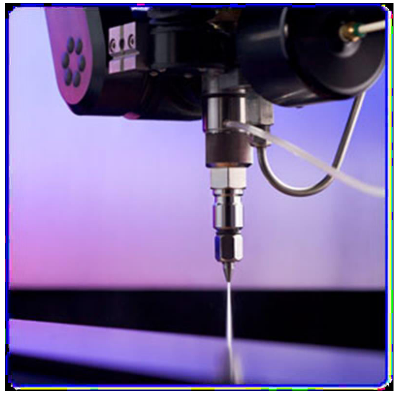
Abrasive jet machining (AJM)



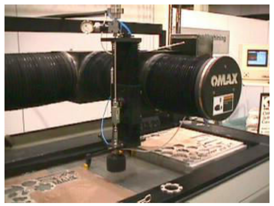
- Fine abrasive particles with high kinetic energy (KE) hit the workpiece at an angle and remove the material in the form of micro/nano-chips.
- If the KE of the abrasive particle is high enough, then it will remove the material by shear deformation in case of ductile workpiece material and by brittle fracture if work piece material is brittle.

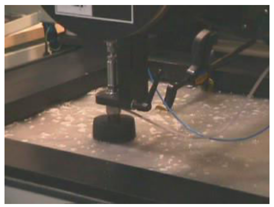
Water Jet Machining

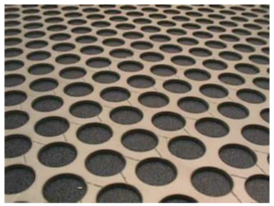
- Pros: no need for predrilled holes, no heat, no workpiece deflection (hence suitable for flexible materials), minimal burr, environmentally friendly.
- Cons: limited to material with naturally occurring small cracks or softer material.
- Applications:
  - Mostly used to cut lower strength materials such as wood, plastics, rubber, paper, leather, composite, etc.
  - Food preparation
  - Good for materials that cannot withstand high temperatures of other methods for stress distortion or metallurgical reasons.

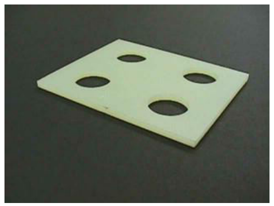


Examples: Abrasive Water-jet & Water-jet machining

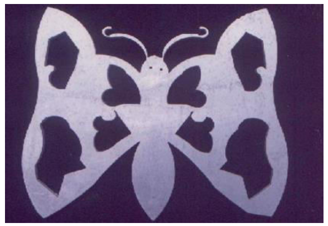






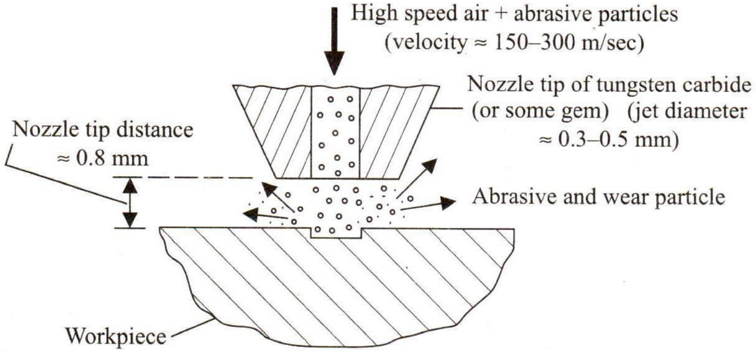


Applications of AJM



Granite cutting by Abrasive Water jet machining (IIT M)

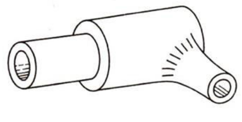
Abrasive jet machining (AJM)



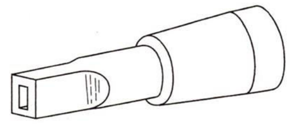
- Popular for brittle materials – Glass, ceramic, quartz
- Material removal due to tiny fracture caused by the impingement of fine abrasive particles with compressed (several atmospheric pressure) high speed air stream
- Abrasive particles: 25-50 μm

AJM - Process parameters

- The process characteristics can be evaluated by judging
  - the material removal rate (MRR)
  - the geometry of the cut
  - the roughness of the surface produced
  - the rate of nozzle wear.
- The major parameters which control these quantities are:
  - Abrasive (composition, strength, size and mass flow rate).
  - Gas (composition, pressure and velocity).
  - Nozzle (geometry, material, distance from and inclination to the work surface)
- Abrasive: Alumina (Al_2O_3), SiC
- Gas medium : dry air
- Nozzle : WC, Sapphire
- Nozzle shape: straight



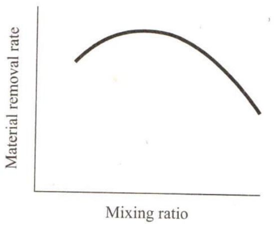
(a) Right angle head

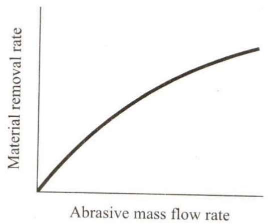


(b) Straight head

Abrasive used in AJM

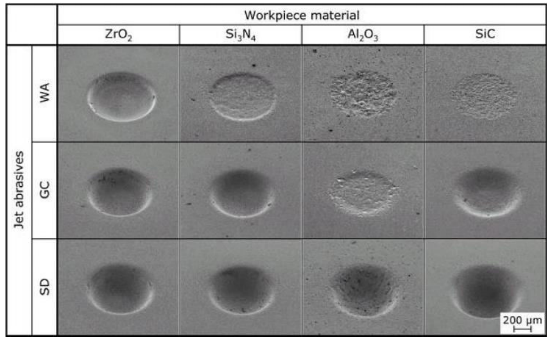
- Mainly two types of abrasives are used (1) Aluminum oxide and (2) Silicon carbide. (Grains with a diameter 10-50 microns are readily available)
- For good wear action on the surfaces the abrasive grains should have sharp edges.
- A reuse of the abrasive powder is normally not recommended because of a decrease of cutting capacity and clogging of the nozzle orifices due to contamination.
- The mass flow rate of the abrasive particles depends on the pressure and the flow rate of the gas.

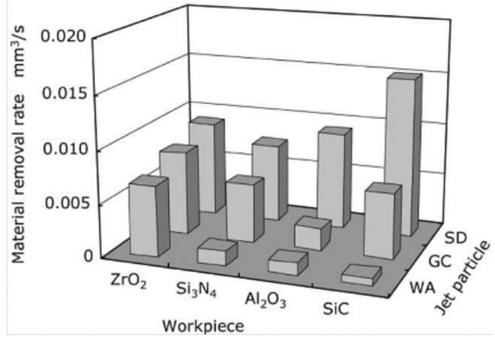




- There is an optimum mixing ratio (mass fraction of the abrasive) for which the metal removal rate is the highest.
- When the mass flow rate of the abrasive increases the material removal rate also increases.

Effect of different abrasives



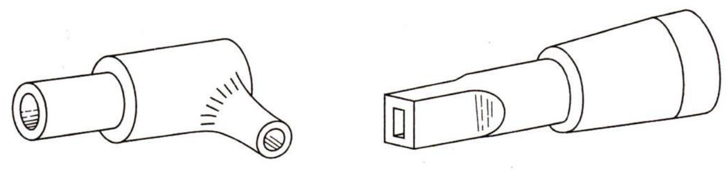


WA – Alumina, GC – Silicon carbide, SD – Synthetic diamond

- Appearance of the dimples during AJM for 10 s. for various machining sets of abrasives and ceramic materials.

Gas medium and Nozzle

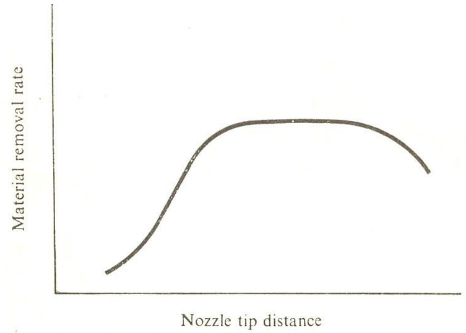
- The AJM unit normally operates at a pressure of 0.2-1.0 N/mm2 .
- The composition of gas and a high velocity has a significant impact on the MRR even if the mixing ratio is not changed.
- The nozzle is one of the most vital elements controlling the process characteristics.
- The nozzle material should be hard to avoid any significant wear due to the flowing abrasive. [Normally WC (avg. life: 12-30 hrs.) or Sapphire (Appr. = 300 hrs.) are used]
- For a normal operation the cross-sectional area of the orifice can be either circular or rectangular and between 0.05- 0.2mm^2 .

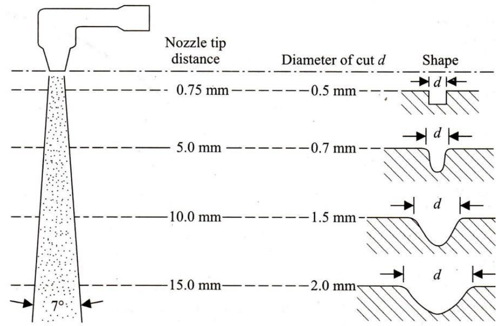


(a) Right angle head (b) Straight head

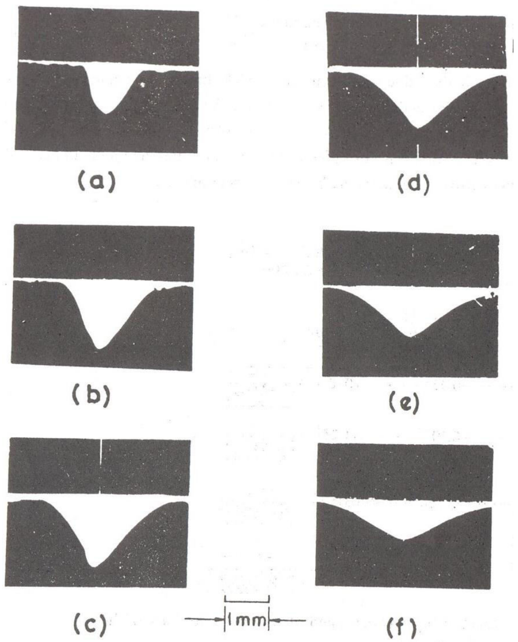
Nozzle to tip distance (Stand off distance)

- Nozzle tip distance (NTD) or stand off distance is a critical parameter in AJM.
- NTD affects the MRR from the work surface, the shape and size of the cavity produced.
  - In beginning Velocity of the abrasive particles impinging on the work surface increases due to their acceleration after they leave the nozzle. This increases the MRR.
  - When NTD increased further, velocity reduces due to the drag of the atmosphere , and thus MRR decreases it.





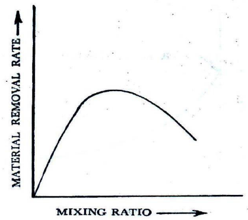
Photographs of the Machined Cavity at different NTD

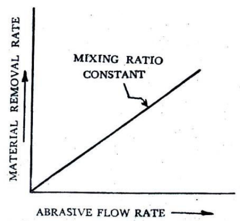


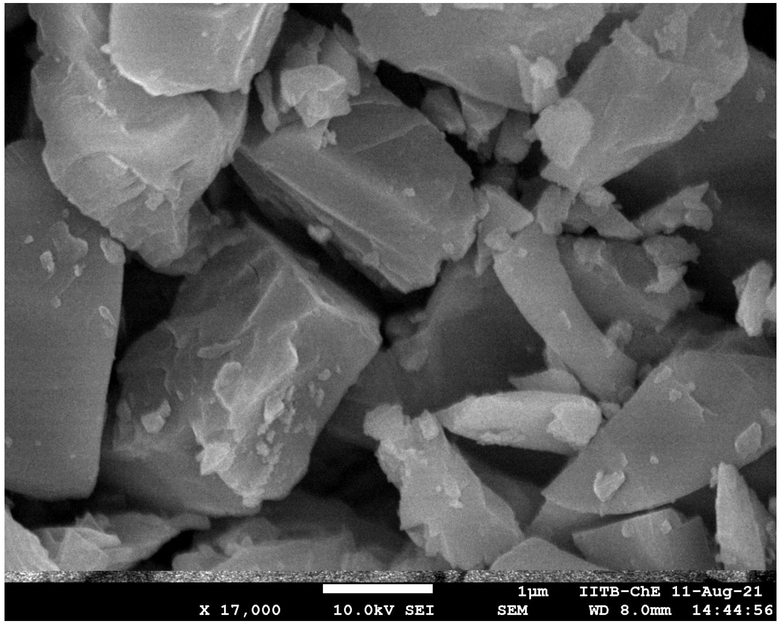
- Profile of the machined cavity at different stand off distances
- (a) 2mm (b) 6mm (c) 10mm
- (d) 14mm (e) 16mm (f) 20mm

Effect of mixing ratio and mass ratio

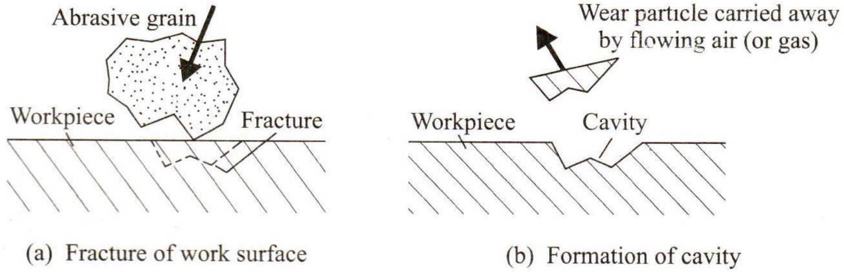
- Increased mass flow rate of abrasive will result in reduced velocity of fluid
  - Reduced available energy for erosion and thus MRR.
  - $Mixing\ Ratio = \frac{Volume\ flow\ rate\ of\ abrasive}{Volume\ flow\ rate\ of\ carrier\ medium}$
- The mixing ratio is unchanged only by simultaneous increase of both gas and abrasive flow rate.
- In some cases, instead of mixing ratio, mass ratio (α) is also used
- $Mass\ Ratio = \frac{Mass\ flow\ rate\ of\ carrier\ medium}{Mass\ flow\ rate\ of\ (carrier\ medium + abrasive)}$







Mathematical model of AJM



(a) Fracture of work surface (b) Formation of cavity

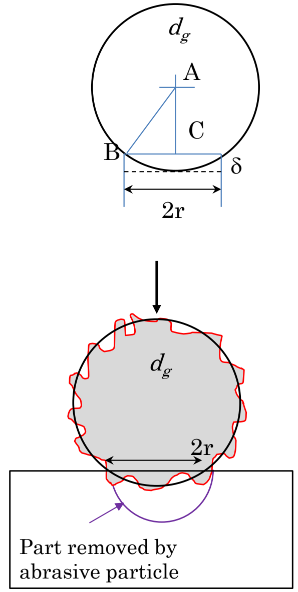
- AJM is more suitable when the work material is brittle and fragile.
- A model for the material removal rate (MRR) is available [Sarkar and Pandey, 1980].
- MRR $Q = \chi Z d^3 v^{3/2} \left(\frac{\rho}{12H_w}\right)^{3/4}$
  - Z : No of particles impacting per unit time
  - d: mean diameter of abrasive particle
  - v: velocity of abrasive grains
  - ρ: density of abrasive
  - H_w: hardness of workpiece material

Modeling of abrasive jet machining process

- Assumptions:
  - Abrasive are spherical in shape and rigid (exact sharp edges are difficult to predict)
  - No loss of kinetic energy of abrasive particles, i.e., complete transfer of Kinetic energy of abrasive particles into material removal
  - Brittle material are failed due to brittle fracture
  - Fracture of volume is considered to be hemispherical with diameter equal to chordal length of indentation
  - In ductile material volume of material removal is assumed to be equal to indentation volume due to particulate impact.

MRR by AJM – brittle material

- If δ is the indentation depth, d_g is the diameter of the abrasive grain, and r is the radius of indented area
- $r^2 = d_g\delta - \delta^2,\ r^2 \sim d_g\delta$
- Fracture volume is considered to be hemispherical with diameter equal to chordal length of indentation
- Volume of the material removed in brittle material caused by the fracture and microcracks
- $Vol = \frac{2}{3}\pi r^3 = \frac{2}{3}\pi (d_g\delta)^{3/2}$
- For brittle materials: complete conversion of kinetic energy (KE) into the material removal
- $KE = \frac{1}{2}mV^2 = \frac{1}{2}\left[\left(\frac{\pi}{6}d_g^3\rho_g\right)V^2\right]$
- ρ_g density of the abrasive grains



MRR by Single abrasive particle

- Upon impact, work material is subjected to a equivalent force F, which will lead to indentation depth δ
- As the force F will vary as per the indentation depth (from zero to maximum value at δ)
- The work done during the indentation by a single abrasive will be : $\frac{1}{2}F\delta$
- If σ_w is the fracture strength of the work piece material , then Force F would be:
- $F = \sigma_w(\pi r^2), F = \sigma_w \pi (d_g \delta)$
- Work done $W = \frac{1}{2}F\delta = \frac{1}{2}\sigma_w \pi d_g \delta^2$
- As the KE = Work done. $\frac{1}{2}\left[\left(\frac{\pi}{6}d_g^3\rho_g\right)V^2\right] = \frac{1}{2}\sigma_w \pi d_g \delta^2$
- $\delta^2 = \frac{\rho_g}{6\sigma_w} V d_g$
- V is the speed of abrasive particles

MRR by Single abrasive particle

- Material removal rate (MRR) in AJM can be expressed as:
- MRR = Volume removed by single abrasive x Number of impacts made by abrasive per second
- MRR = Vol $* \left(\frac{mass\ flow\ rate\ of\ abrasive}{mass\ of\ the\ abrasive\ grit}\right)$
- $MRR = \frac{2}{3}\pi(d_g\delta)^{3/2} * \frac{M_a}{\frac{1}{6}\pi(d_g)^3\rho_g}$
- $MRR = \frac{4Ma}{\rho_g}\left(\frac{\delta}{d_g}\right)^{3/2}$
- M_a mass flow rate of abrasive

For ductile material – MRR by AJM

- Volume of removed material by single abrasive particle
- $Vol = \frac{\pi}{2} d_g \delta^2$
- MRR = Volume removed by single abrasive x Number of impacts made by abrasive per second
- $MRR = \frac{\pi}{2} d_g \delta^2 * \frac{M_a}{\frac{1}{6}\pi(d_g)^3\rho_g}$
- $MRR = \frac{3Ma}{\rho_g}\left(\frac{\delta}{d_g}\right)^2$
- M_a mass flow rate of abrasive