2.0 INTRODUCTION

In abrasive jet machining, a focused stream of abrasive particles, carried by high pressure air or gas is made to impinge on the work surface through a nozzle and work material is removed by erosion by high-velocity abrasive particles. The AJM differs from sandblasting. In AJM the abrasive is much finer and the process parameters and cutting action are carefully controlled.

<table>
<thead>
<tr>
<th>Sand Blasting</th>
<th>Abrasive Jet Machining</th>
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</thead>
<tbody>
<tr>
<td>Sand blasting is an act of propelling very fine bits of material at high velocity to clean or etch a surface.</td>
<td>In AJM, a focused steam of abrasive particles carried by high pressure gas is used.</td>
</tr>
<tr>
<td>Uniform particles of sand, steel grit, copper slag, walnut shells, and powdered abrasives are used.</td>
<td>Silicon carbide, aluminium oxide, glass beads, dolomite, sodium bicarbonate are used as abrasives.</td>
</tr>
<tr>
<td>In sand blasting abrasives are sprayed all over usually for cleaning surfaces from corrosion, paints, glues and other contaminants.</td>
<td>AJM is not only used for cleaning but also for cutting, deburring, deflashing, etc. AJM is a well controlled process compared to sand blasting.</td>
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</tbody>
</table>

AJM is mainly used to cut intricate shapes in hard and brittle materials which are sensitive to heat and chip easily. The process is also used for deburring and cleaning operations. AJM is inherently free from chatter and vibration problems. The cutting action is cool because the carrier gas serves as a coolant.

2.1 PROCESS

Schematic diagram of abrasive jet machining is shown in Figure 2.0. In abrasive jet machining abrasive particles are made to impinge on the work material at high velocity. Jet of abrasive particles is carried by carrier gas or air. The high velocity stream of abrasives is generated by converting pressure energy of the carrier gas or air to its kinetic energy and hence high-velocity jet. Nozzles direct the abrasive jet in a controlled manner onto the work material. The high-velocity abrasive particles remove the material by micro-cutting action as well as brittle fracture of the work material.

AJM is a process of removal of material by impact erosion through the action of concentrated high-velocity stream of grit abrasives entrained in high velocity gas stream. AJM is different from shot or sand blasting, as in AJM, finer abrasive grits are used and parameters can be controlled more effectively providing better control over product quality.
nozzle is made of either circular or rectangular cross section and head can be straight, or at a right angle. It is so designed that loss of pressure due to the bends, friction, etc., is minimum possible. With increase in wear of a nozzle, the divergence of jet stream increases resulting in more stray cutting and high inaccuracy.

Desired properties of materials used for nozzle

1. Material has to withstand the erosive action of abrasive particles.
2. It should have good wear resistance properties: Increase in wear of the nozzle leads to divergence of jet stream. Divergence of jet steam causes stray cutting and inaccurate holes.
3. It should have good resistance to corrosion.
4. It should be designed such that loss of pressure due to bend and friction is minimum.

(e) Abrasives Used: Aluminium oxide (Al₂O₃) silicon carbide (SiC) glass beads, crushed glass and sodium bicarbonate are some of abrasives used in AJM. Selection of abrasives depends on MRR, type of work material, and machining accuracy. Table 2.1 gives classification of abrasives and its applications.
### Table 2.1 Abasives used in AJM and its applications

<table>
<thead>
<tr>
<th>Abasives</th>
<th>Grain Sizes</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium oxide (Al$_2$O$_3$)</td>
<td>12, 20, 50 microns</td>
<td>Good for cleaning, cutting and deburring</td>
</tr>
<tr>
<td>Silicon carbide (SiC)</td>
<td>25, 40 microns</td>
<td>Used for similar applications but for hard materials</td>
</tr>
<tr>
<td>Glass beads</td>
<td>0.635 to 1.27 mm</td>
<td>Gives matte finish</td>
</tr>
<tr>
<td>Dolomite</td>
<td>200 mesh</td>
<td>Etching and polishing</td>
</tr>
<tr>
<td>Sodium bicarbonate</td>
<td>27 microns</td>
<td>Cleaning, deburring and cutting of soft material. Light finishing below 500°C</td>
</tr>
</tbody>
</table>

**Desired properties of abrasives used in AJM**

1. Abrasives should have sharp and irregular shape.
2. It should be fine enough to remain suspended in the carrier gas.
3. In addition to hardness, the important properties of an abrasive is friability. Friability is the ability of abrasive grains to fracture into smaller pieces; this property gives abrasives self sharpening characteristic. High friability indicates low strength or low fracture resistance of the abrasives. High friable abrasives fragment more rapidly than lower friable abrasives. Aluminium oxide has lower friability than silicon carbide; hence it has less tendency to fracture.
4. Should be cheap and easily available.
5. It should have excellent flow characteristics.

Silicon carbide and aluminium oxide are used for cutting operation. Sodium bicarbonate, dolomite, glass beads are used for cleaning, etching, deburring and polishing applications.

Reuse of abrasives is not recommended because:
1. Cutting capacity decreases after first use.
2. Contamination clogs the small orifices in the nozzle.

### 2.3 PROCESS PARAMETERS

For successful utilization of AJM process, it is necessary to analyze the following process criteria.
1. Material removal rate.
2. Geometry and surface finish of the workpiece.
3. Wear rate of the nozzle.

However, process criteria are generally influenced by the process parameters as enumerated below:

- **Abrasives**
  - Material: Al$_2$O$_3$, SiC, Glass beads, crushed glass, sodium bicarbonate
  - Shape: irregular/regular
(c) Size: 10 to 50 microns
(d) Mass flow: 2-20 grams/min

- **Carrier Gas**
  (a) Composition: Air, CO₂, N₂
  (b) Density: 1.3 kg/m³
  (c) Velocity: 500 to 700 m/s
  (d) Pressure: 2 to 10 bars
  (e) Flow rate: 5 to 30 microns

- **Abrasive Jet**
  (a) Velocity: 100 to 300 m/s
  (b) Mixing ratio: Volume flow rate of abrasives/Volume flow rate of gas
  (c) Stand-off distance: SOD- 0.5 to 15 mm.
  (d) Impingement angle: 60 to 90 deg.

- **Nozzle**
  (a) Material: WC/ Sapphire
  (b) Diameter: 0.2 to 0.8 mm
  (c) Life: 300 hours for sapphire, 20 to 30 hours for WC

### 2.4 PROCESS CAPABILITIES

1. Material removal rate: 0.015 cm³/min
2. Narrow slots: 0.12 to 0.25 mm ± 0.12 mm
3. Surface finish: 0.25 micron to 1.25 microns
4. Sharp radius up to 0.2 mm is possible.
5. Steel up to 1.5 mm, glass up to 6.3 mm is possible to cut.
6. Machining of thin sectioned hard and brittle materials is possible.

### 2.5 APPLICATIONS OF AJM

1. AJM is used for abrading and frosting glass, ceramics and refractories more economically as compared to etching or grinding.
2. Cleaning of metallic smears on ceramics, oxides on metals, resistive coating, etc.
3. AJM is useful in manufacture of electronic devices, drilling of glass wafers, deburring of plastics, making of nylon and teflon parts, permanent marking on rubber stencils, cutting titanium foils.
4. Deflashing small castings and trimming of parting lines of injection moulded parts and forgings.
5. Use for engraving registration numbers on toughened glass used for car windows.
6. Used for cutting thin fragile components like germanium, silicon, quartz, mica, etc.
7. Micro module fabrication for electrical contact, semiconductor processing can be done effectively.
8. Used for drilling, cutting, deburring etching and polishing of hard and brittle materials.
9. Most suitable for machining brittle and heat-sensitive materials like glass, quartz, sapphire, mica, ceramics, germanium, silicon and gallium.
10. It is also good for deburring small holes like in hypodermic needles and for small milled slots in hard metallic components.
11. It can be used for micromachining of brittle materials.
12. It is used in fine drilling and aperture drilling for electronic microscope.
13. Used for cleaning metallic moulds and cavities.
14. Cleaning surfaces from corrosion, paints, glues and other contaminants, especially those that are inaccessible.
15. Deburring of surgical needles and hydraulic valves, nylon, teflon and derlin.
16. Engraving on glass using rubber or metallic masks.

2.6 ADVANTAGES OF AJM
1. High surface finish can be obtained depending upon the grain sizes.

<table>
<thead>
<tr>
<th>Particle Size (in Microns)</th>
<th>Surface Roughness (in Microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.152 to 0.203</td>
</tr>
<tr>
<td>25 to 27</td>
<td>0.355 to 0.675</td>
</tr>
<tr>
<td>50</td>
<td>0.965 to 1.27</td>
</tr>
</tbody>
</table>

2. Depth of damage is low (around 2.5 microns).
3. It provides cool cutting action, so it can machine delicate and heat-sensitive material such as glass and ceramics. They can be machined without affecting their physical properties and crystalline structure.
4. Process is free from chatter and vibration as there is no contact between the tool and the workpiece.
5. Capital cost is low and it is easy to operate and maintain AJM.
6. Thin sections of hard brittle materials like germanium, mica, silicon, glass and ceramics can be machined.
7. It has the capability of cutting holes of intricate shape in hard and brittle materials.
8. Abrasive jet process produces surfaces which have high wear resistance.

2.7 DISADVANTAGES OF AJM
1. Limited capacity due to low MRR. MRR for glass is 40 gm/minute.
2. Abrasives may get embedded in the work surface, especially while machining soft material like elastomers or soft plastics.
3. The accuracy of cutting is hampered by tapering of hole due to unavoidable flaring of abrasive jet.
4. Stray cutting is difficult to avoid and hence accuracy is not good.
5. A dust collection system is a basic requirement to prevent atmospheric pollution and health hazards.
6. Nozzle life is limited (300 hours).
7. Abrasive powders cannot be reused as the sharp edges are worn and smaller particles can clog the nozzle.
8. Short stand-off distances when used for cutting, damages the nozzle.
9. The process accuracy is poor because of flaring effect of the abrasive jet.
10. Deep holes will have unacceptable taper.
12. Some hazard is involved in using AJM process because of airborne abrasive particulates. By using abrasive water jet machining this problem can be solved.

2.8 MACHINING CHARACTERISTICS OF AJM

Following are the AJM process criteria:
1. Material removal rate
2. Geometry and surface finish of the workpiece
3. Wear rate of the nozzle

Process criteria are generally influenced by the process parameters.

The characteristics of the above process parameters on process criteria are as follows.

1. **Effect of abrasive flow rate and grain size on MRR** (Figure 2.2)

   It is clear from the figure that at a particular pressure MRR increases with increase in abrasive flow rate and is influenced by the size of the abrasive particles. But after reaching optimum value, MRR decreases with further increase in abrasive flow rate. This
is owing to the fact that mass flow rate of gas decreases with increase of abrasive flow rate and hence mixing ratio increases causing a decrease in material removal rate because of decreasing energy available for erosion.

2. **Effect of exit gas velocity and abrasive particle density** (Figure 2.3)
The velocity of carrier gas conveying the abrasive particles changes considerably with the change of abrasive particle density as indicated in figure.

![Figure 2.3 Effect of exit gas velocity and abrasive particle density.](image)

The exit velocity of gas can be increased to critical velocity when the internal gas pressure is nearly twice the pressure at exit of nozzle for the abrasive particle density is zero. If the density of abrasive particles is gradually increased exit velocity will go on decreasing for the same pressure condition. It is due to the fact that kinetic energy of gas is utilized for transporting the abrasive particles.

3. **Effect of mixing ratio on MRR**
Increased mass flow rate of abrasive will result in a decreased velocity of fluid and will thereby decreases the available energy for erosion and ultimately the MRR. It is convenient to explain this fact by term mixing ratio. Which is defined as

\[
\text{Mixing ratio} = \frac{\text{Volume flow rate of abrasives per unit time}}{\text{Volume flow rate of carrier gas per unit time}}
\]

The effect of mixing ratio on the material removal rate is shown in Figure 2.4.

The material removal rate can be improved by increasing the abrasive flow rate provided the mixing ratio is kept constant. The mixing ratio is unchanged only by simultaneous increase of both gas and abrasive flow rate (Figure 2.5).

An optimum value of mixing ratio that gives maximum MRR is predicted by trial and error. In place of mixing ratio, the mass ratio \( \alpha \) may be easier to determine. Which is defined as

\[
\alpha = \frac{\text{Volume flow rate of abrasives}}{\text{Volume flow rate of carrier gas}} = \frac{m_a}{m_a + m_g}
\]
4. **Effect of nozzle pressure on MRR** (Figure 2.6)

The abrasive flow rate can be increased by increasing the flow rate of the carrier gas. This is only possible by increasing the internal gas pressure as shown in the figure. As the internal gas pressure increases abrasive mass flow rate increases and thus MRR increases.

As a matter of fact, the material removal rate will increase with the increase in gas pressure.

Kinetic energy of the abrasive particles is responsible for the removal of material by erosion process. The abrasive must impinge on the work surface with minimum velocity for machining glass by SIC particle is found to be around 150 m/s. (Figure 2.7)
1. Abrasives are spherical in shape and rigid.
2. Kinetic energy of particle is used to cut the material.
3. Brittle materials are considered to fail due to brittle fracture and fracture of volume is considered to be hemispherical with diameter equal to chordal length of indentation.
4. For ductile material volume of material removal is assumed to be equal to the indentation volume due to particulate impact.

Abrasive particles are assumed to be spherical in shape having diameter $d_g$

From the geometry (Figure 2.10)

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

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

---

**Figure 2.8** Effect of stand-off distance on the width of the cut.

**Figure 2.9** Effect of stand-off distance on material removal rate and penetration rate.
Neglecting $d^2$ term, we can write

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

For Brittle material

Volume of the material removed is the volume of the hemispherical crater due to fracture. Volume of the material removed is given by:

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

Let us assume that grits also move with velocity $(V)$ then we can write

Kinetic energy $= KE = \frac{1}{2} MV^2$

$M =$ mass of a single abrasive grit $= $ volume of grit $\times$ density of grit
Volume of single grit = \( \frac{4\pi r_g^3}{3} = \frac{4\pi}{3} \left( \frac{d_g}{2} \right)^3 = \frac{\pi (d_g)^3}{6} \)

Therefore, we can write kinetic energy of the single grit

\[
KE = \frac{1}{2} MV^2 = \frac{1}{2} \left( \frac{\pi (d_g)^3}{6} \right) \rho_g V^2
\]

(2)

On impact, work material would be subjected to maximum force \( F \), which would lead to indentation of \( \delta \).

Work done during such indentation is

\[
WD \text{ by the grit} = \frac{F \delta}{2}
\]

(3)

Also we know the flow strength of material = \( \sigma_w = \frac{F}{\pi r^2} \)

\[
F = \sigma_w \times \pi r^2
\]

\[
F = \sigma_w \times \pi d_g \delta
\]

(4)

Using equation (4) in (3), we get

\[
WD \text{ by the grit} = \frac{F \delta}{2} = \frac{\sigma_w \times \pi d_g \delta \times \delta}{2}
\]

It is assumed that kinetic energy of the abrasives is fully used for material removal. Kinetic energy of the particle = WD by the particle

\[
\frac{1}{2} \left( \frac{\pi (d_g)^3}{6} \rho_g \right) V^2 = \frac{\sigma_w \times \pi d_g \delta \times \delta}{2}
\]

Simplifying, we get

\[
\delta = V d_g \sqrt{\frac{\rho_g}{6 \sigma_w}}
\]

(5)

MRR in AJM material can be expressed as

\[
MRR = \Gamma_B \times \left[ \frac{\text{Mass flow rate of abrasives}}{\text{Mass of the abrasive grit}} \right]
\]

\[
\times \text{Number of impacts made by abrasives per second}
\]

\[
MRR = \Gamma_B \times \left[ \frac{\text{Volume of material removed per grit per cycle}}{\text{Mass of the abrasive grit}} \right]
\]
Abrasives grain density $\rho_g = 3 \text{ grams/cc} = \frac{3 \times 10^{-3}}{10^{-6}} \text{ kg/m}^3 = 3 \times 10^3 \text{ kg/m}^3$

Mass flow rate of abrasives $M_a = \frac{2.5 \text{ grams}}{\text{min}} = \frac{2.5 \times 10^{-3}}{60} \text{ kg/sec}$
Velocity $= 205 \text{ m/sec}$

**Solution:** Since the material is brittle. We need to use the MRR formula corresponding to the brittle material.

$$
\text{MRR} = \left[ \frac{M_a (V)^{3/2}}{(\sigma_w)^{1/4} (\rho_g)^{1/4}} \right]
$$

$$
\text{MRR} = \left[ \frac{2.5 \times 10^{-3} / 60 \times (205)^{3/2}}{(3 \times 10^9)^{3/4} (3 \times 10^3)^{1/4}} \right]
$$

$$
\text{MRR} = 1.289 \times 10^{-9} \text{ m}^3/\text{sec} = 77.35 \text{ mm}^3/\text{min}
$$

**Problem 2.2** Material removal rate in AJM is $0.5 \text{ mm}^3/\text{sec}$. Calculate MRR/impact if the mass flow rate of abrasive is $3 \text{ gm/min}$, density is $3 \text{ gm/cc}$ and grit size is $60 \text{ microns}$. Also calculate the indentation radius.

**Data Given:**
Material removal rate $= 0.5 \text{ mm}^3/\text{sec}$.
Abrasives grain size $= 50 \text{ microns} = 50 \times 10^{-3} \text{ mm}$
Abrasives grain density $\rho_g = 3 \text{ grams/cc} = \frac{3 \times 10^{-3}}{10^{-6}} \text{ kg/m}^3 = 3 \times 10^3 \text{ kg/m}^3$
Mass flow rate of abrasives $M_a = 3 \text{ gm/min} = 3 \times 10^{-7}/60 \text{ kg/sec}$

**Solution:**

Volume of single grit $= \frac{4 \pi r_g^3}{3} = \frac{4 \pi \left( \frac{d_g}{2} \right)^3}{3} = \frac{\pi (d_g)^3}{6}$

Mass of single grit $= \frac{\pi (d_g) \rho_g^3}{6} = \frac{\pi (50 \times 10^{-3}) \left( \frac{3 \times 10^{-3}}{60} \right)^3}{6}$

MRR in AJM material can be expressed as

$$
\text{MRR} = \{ \text{Volume of material removed per grit per cycle} \} \times \text{Number of impacts made by abrasives per second}
$$
Number of impacts made by abrasives per second \( (N) \)

\[
N = \frac{M_a}{\text{Mass of the abrasive grit}} = \frac{3 \times 10^{-3}}{60 \pi (50 \times 10^{-3}) (3000)/6} = 254648 \text{ impacts/s}
\]

\[0.5 = \left\{ \text{Volume of material removed per grit per cycle} \right\} \times \text{Number of impacts made by abrasives per second}\]

\[0.5 = \left\{ \text{Volume of material removed per grit per cycle} \right\} \times 254648\]

\[0.5 = \Gamma_b \times 254648\]

\[\Gamma_b = \text{Volume of material removed per grit} = \left[ \frac{0.5}{254648} \right] = 1.96 \times 10^{-6} \text{ mm}^3\]

\[= 1960 \mu \text{m}^3\]

Indentation volume

\[
\frac{1}{2} \left( \frac{4\pi r_g^3}{3} \right) = \frac{1}{2} \left[ \frac{4\pi \left( \frac{d_g}{2} \right)^3}{3} \right] = \frac{\pi \left( d_g \right)^3}{12} = 1960
\]

Solving, we get

\[d_g = 19.56 \text{ microns}\]

**Problem 2.3** During AJM, mixing ratio used is 0.2. Calculate mass ratio, if the ratio of density of abrasives and density of carrier gas is equal to 20.

**Solution:**

Mixing ratio

\[
\text{Mixing ratio} = \frac{\text{Volume flow rate of abrasive particles}}{\text{Volume flow rate of carrier gas}} = \frac{V_g}{V_a} = 0.2
\]

Mass ratio \((\alpha)\)

\[
\text{Mass ratio (}\alpha\text{)} = \frac{\text{Abrasive mass flow rate}}{\text{Combined mass flow rate of abrasive and carrier gas}}
\]

\[
\text{Mass ratio (}\alpha\text{)} = \frac{M_a}{M_a + M_g} = \frac{\rho_a \ V_a}{\rho_a \ V_a + \rho_g \ V_g}
\]

We can rewrite the expression for mass ratio as

\[
\frac{1}{\alpha} = \frac{M_a + M_g}{M_a} = \frac{\rho_a \ V_a + \rho_g \ V_g}{\rho_a \ V_a} = 1 + \left[ \frac{\rho_g}{\rho_a} \right] \left[ \frac{V_g}{V_a} \right] = 1 + \left[ \frac{1}{20} \right] \left[ \frac{1}{0.2} \right]
\]

Solving, we get \(\alpha = 0.80\)