Water Jet Machining (WJM)/ Abrasive Water Jet Machining (AWJM)

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Waterjet Pumps: Direct Drive vs Intensifier

OMAX Direct Drive

Standard Intensifier

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Introduction

- WJM - suitable for cutting plastics, foods, rubber insulation, automotive carpeting and headliners, and most textiles.
- Harder materials such as glass, ceramics, concrete, and tough composites can be cut by adding abrasives to the water jet.
- Abrasive water jet machining (AWJM) - Developed in 1974 to clean metal prior to surface treatment of the metal.
- The addition of abrasives to the water jet enhanced MRR and produced cutting speeds between 51 and 460 mm/min.
- Generally, AWJM cuts 10 times faster than the conventional machining methods of composite materials.
- Zheng et al. (2002) claimed that the abrasive water jet is hundreds of times more powerful than the pure water jet.
Different approaches and methodologies in WJM & AWJM

- WJM – pure
- WJM – with stabilizer
- AWJM – entrained – three phase (water + air + abrasives)
- AWJM – suspended – two phase (water + abrasives)

- Direct pumping
- Indirect pumping
- Bypass pumping

*In all the above variants, the basic methodology remains the same.*
Methodology

- Water is pumped at a sufficiently high pressure, 200-400 MPa (2000 – 4000 bar).
- “Intensifier” works on the principle of pressure amplification using hydraulic cylinders of two different cross-sections.
- When water at such a pressure is passed through a suitable orifice (nozzle having $\phi = 0.2 – 0.4$ mm), the potential energy of water is converted into kinetic energy.
- This yields high velocity ($\sim 1000$ m/s) jet of water.
- Such a high velocity water jet can machine thin sheets/foils of aluminium, leather, textile, frozen foods, etc.
- WJM – commercially pure water (tap water) is used for machining.
Variants in WJM & AWJM

- Problem in WJM – as the high velocity water jet is discharged from the orifice, the jet tends to entrain atmospheric air and flares out – decreasing the machining ability.
- Hence, stabilizers (long chain polymers) are added to water (WJM with stabilizer).
- Stabilizers hinders the fragmentation of water jet.
- In AWJM, abrasive particles are added to the water jet to enhance its cutting ability by many folds.
- In entrained type AWJM, the abrasive particles are allowed to entrain in water jet to form abrasive water jet with sufficient velocity of as high as 800 m/s.
- Such high velocity abrasive jet can machine almost any material.
WJM & AWJM - Applications

- Paint removal
- Cleaning
- Cutting soft materials
- Cutting frozen meat
- Textile, Leather industry
- Mass Immunization
- Surgery
- Peening
- Pocket Milling
- Drilling & Turning
- Nuclear Plant Dismantling
Applications of WJM & AWJM

- The cutting ability of WJM can be improved drastically by adding hard and sharp abrasive particles into the water jet.
- Thus, WJM is typically used to cut so called “softer” and “easy-to-machine” materials like thin sheets and foils, non-ferrous metallic alloys, wood, textiles, honeycomb, polymers, frozen meat, leather etc.
- But, the domain of “harder” and “difficult-to-machine” materials like thick plates of steels, aluminium and other commercial materials, metal matrix and ceramic matrix composites, reinforced plastics, layered composites, etc. are reserved for AWJM.
- Other than cutting (machining) high pressure water jet also finds application in paint removal, cleaning, surgery, peening to remove residual stress etc.
- AWJM can as well be used besides cutting for pocket milling, turning, drilling, etc.
- One of the strategic areas where “robotic AWJM” is finding critical application is dismantling of nuclear plants.
Different components machined with AWJM

(Photographic Courtesy - Omax corporation, USA)
WJM & AWJM - Advantages

- Extremely fast set-up and programming
- Very little fixturing for most parts
- Machine virtually any 2D shape on any material
- Very low side forces during the machining
- Almost no heat generated on the part
- Can machine thick plates
AWJM - Elements

- AWJM accelerates a jet of water (70 percent) and abrasive (30 percent) from 4.2 bar up to a velocity of 30 m/s.
- Silicon carbides, sand (SiO₂), corundum, and glass beads of grain size 10 to 150 μm are often used as abrasive materials.
- Using such a method, burrs of 0.35 mm height and 0.02 mm width left in steel component after grinding are removed by the erosive effect of the abrasives while water acts as an abrasive carrier.
- The introduction of compressed air to the water jet enhances the deburring action.
AWJM - Elements

Water 70%

Abrasives 30%

Control valve and variable mixer

Nozzle

Workpiece
Machining System

- In AWJM, the water jet accelerates abrasive particles, to cause the material removal.
- After the pure water jet is created, abrasives are added using either the injection or suspension methods.
- The important parameters of the abrasives are the material structure and hardness, grain shape, size, and distribution.
- The basic machining system of AWJM incorporates the following Elements.

  - Water delivery
  - Abrasive hopper and feeder
  - Intensifier
  - Filters
  - Mixing chamber
  - Cutting nozzles
  - Catcher
Schematic Setup of AWJM

1. LP Booster
2. Hydraulic drive
3. Additive mixer
4. Direction control
5. Intensifier
  5A. LP Intensifier
  5B. HP Intensifier
6. Accumulator

Point A
Injection & Suspension Heads

Diagram:
- Water
- Pressure generation
- Abrasive reservoir
- Machining head
- Focusing tube
- Workpiece
- Side feed
- Central feed
- Water nozzle
- Abrasive storage
- Slurry
- Suspension nozzle
- Suspension
Injection & Suspension Heads

Single Jet, side feed

Multiple jet, central feed
Intensifier – driven by a hydraulic power pack.

Heart of hydraulic power pack is a positive displacement hydraulic pump.

The power packs in modern commercial systems are often controlled by microcomputers to achieve programmed rise of pressure, etc.

Hydraulic power pack – delivers hydraulic oil at a pressure $p_h$ to Intensifier.
• Ratio of cross-section of the two cylinders, \( A_{\text{ratio}} = \frac{A_{\text{large}}}{A_{\text{small}}} \)

• Thus, pressure amplification at the small cylinder takes place as follows:

\[
\begin{align*}
    p_h \times A_{\text{large}} &= p_w \times A_{\text{small}} \\
    p_w &= p_h \times \frac{A_{\text{large}}}{A_{\text{small}}} \\
    p_w &= p_h \times A_{\text{ratio}}
\end{align*}
\]

• Thus, if the hydraulic pressure is set as 100 bar and area ratio is 40, \( p_w = 100 \times 40 = 4000 \) bar.

• By using direction control valve, the intensifier is driven by the hydraulic unit.

• The water may be directly supplied to the small cylinder of the intensifier.
Or it may be supplied through a booster pump, which typically raises the water pressure to 11 bar before the intensifier.

Sometimes water is softened or long chain polymers are added in “additive unit”.

Thus, as the intensifier works, it delivers high pressure water.

As the larger piston changes direction within the intensifier, there would be a drop in the delivery pressure.

To counter such drops, a thick cylinder is added to the delivery unit to accommodate water at high pressure.

This is called an “accumulator” which acts like a “fly wheel” of an engine and minimises fluctuation of water pressure.
Other Elements

- High-pressure water is then fed through the flexible stainless steel pipes to the cutting head.
- Such pipes carry water at 4000 bar (400 MPa) with flexibility incorporated in them with the help of joints, but without any leakage.
- Typical diameter of the flexible stainless steel pipes is of 6 mm.
- Water carried through the pipes is brought to the jet former or cutting head.
- Cutting head consists of orifice, mixing chamber and focusing tube or insert where water jet is formed and mixed with abrasive particles to form abrasive water jet.
Cutting Heads

- High-pressure water
- Orifice
- Abrasive
- Focussing tube
- Cover
**Production of Water Jet**

- The potential or pressure head of the water is converted into velocity head by allowing the high-pressure water to pass through an orifice of small diameter (0.2 – 0.4 mm).

- The velocity of the water jet thus formed can be estimated, assuming no losses as \( v_{wj} = (2p_w / \rho_w)^{1/2} \) using Bernoulli’s equation.

  Where, \( p_w \) and \( \rho_w \) are pressure and density of water respectively.

- The orifices are typically made of sapphire.

- In commercial machines, the life of the sapphire orifice is typically around 100 – 150 hours.

- In WJM this high velocity water jet is used for the required application where as in AWJM it is directed into the mixing chamber.

- Typical mixing chamber - inner diameter 6 mm and a length of 10 mm.

- As the high velocity water is issued from the orifice into the mixing chamber, low pressure (vacuum) is created within the mixing chamber.

- Metered abrasive particles are introduced into the mixing chamber through a port.

- The abrasive particles are metered using different techniques like vibratory feeder or toothed belt feeder.
Mixing Chamber

- Mixing means gradual entrainment of abrasive particles within water jet.
- Finally the abrasive water jet comes out of focusing tube or nozzle.
- During mixing, the abrasive particles are gradually accelerated due to transfer of momentum from water phase to abrasive phase.
- When the jet finally leaves the focusing tube, both phases, water and abrasive, are assumed to be at same velocity.
- Mixing chamber is immediately followed by focusing tube or inserts.
- Focusing tube is generally made of tungsten carbide (powder metallurgy product).
- Typical dimension - inner diameter of 0.8 to 1.6 mm and a length of 50 to 80 mm.
- Tungsten carbide is used for its abrasive resistance.
Abrasive particles during mixing try to enter the jet, but they are reflected away due to interplay of buoyancy and drag force.

They go on interacting with the jet and the inner walls of the mixing tube, until they are accelerated using the momentum of the water jet.

In entrained AWJM, the abrasive water jet, which finally comes from the focussing tube or nozzle, can be used to machine different materials.
Suspension Type AWJM

- In suspension AWJM, the abrasive water jet is formed quite differently.
- There are three different types of suspension AWJ formed by direct, indirect and Bypass pumping method.
- In suspension AWJM, preformed mixture of water and abrasive particles is pumped to a sufficiently high pressure and stored in pressure vessel.
- Then the premixed high-pressure water and abrasive is allowed to discharge from a nozzle to form abrasive water jet.
Suspension Type AWJM
Catcher

- Once the abrasive jet has been used for machining, they may have sufficiently high level of energy depending on the type of application.
- Such high-energy abrasive water jet needs to be contained before they can damage any part of the machine or operators.
- “Catcher” is used to absorb the residual energy of the AWJ and dissipate the same.
- Three types of catcher – water basin type, submerged steel balls and TiB₂ (Titanium Diboride – extremely hard) plate type.
- Moreover the catcher can be of (a) pocket type or (b) line type.
- Pocket type – the catcher basin travels along the jet (along x and y axes).
- Line type – the catcher basin travels along one axis and its length covers the entire width of the other axis of the CNC table.
Catcher

(a) water basin
(b) steel/WC/ceramic balls
(c) catcher plates (TiB₂)
Typical Parameters in Entrained AWJM

- Orifice - Sapphires - 0.1 to 0.3 mm
- Focussing Tube - WC - 0.8 to 2.4 mm
- Pressure - 2500 to 4000 bar
- Abrasive - garnet and olivine - #125 to #60
- Abrasive flow rate - 0.1 to 1.0 kg/min
- Stand off distance - 1 to 2 mm
- Machine Impact Angle - 60° to 90°
- Traverse Speed - 100 mm/min to 5 m/min
- Depth of Cut - 1 mm to 250 mm
Material Removal in AWJM

- Mechanism of material removal in WJM or AWJM is rather complex.
- In AWJ machining of ductile materials, material is mainly removed by low angle impact of abrasive particles.
- Further at higher angle of impact, the material removal involves plastic failure of the material at the sight of impact.
- In AWJ machining of brittle materials, material would be removed due to crack initiation and propagation because of brittle failure of the material.
- In water jet machining, the material removal rate may be assumed to be proportional to the power of the water jet.
Material Removal Rate.

\[ MRR = u \times c_d \times \frac{\Pi}{4} d_o^2 \times \sqrt{\frac{2p_w^3}{\rho_w}} \]

Where

- \( u \) - Constant that depends on the work material
- \( c_d \) - Discharge coefficient of the orifice
- \( d_o \) - Diameter of the orifice
- \( p_w \) - Pressure of water
- \( \rho_w \) - Density of water
Material Removal in AWJM

- The cut generated by an AWJM is called a kerf.
- Top of the kerf ($b_t$) is wider than the bottom of the kerf ($b_b$).
- $b_t$ is equal to the diameter of AWJ or AWJM.
- Diameter of AWJ is equal to the diameter of the focusing tube or the insert if the stand-off distance (SOD) is around 1 to 5 mm.
- Taper angle of the kerf can be reduced by increasing the cutting ability of the AWJ.
Photographic view of kerf (cross section)
Material Removal in AWJM

- Fig. shows the longitudinal section of the kerf.
- It may be observed that the surface quality at the top of the kerf is rather good compared to the bottom part.
- At the bottom there is repeated curved line formation.
- At the top, the material removal is by low angle impact of the abrasive particle; whereas at the bottom, it is by plastic failure.
- Striation formation occurs due to repeated plastic failure.
Material Removal in AWJM

- Fig. shows the exit side of the kerf.
- Though all three of them were machined with the same AWJ diameter, their widths are different due to tapering of the kerf.
- Further, severe burr formation can be observed at the exit side of the kerf.
Thus, in WJM and AWJM the following are the important product quality parameters.

- Striation formation.
- Surface finish of the kerf.
- Tapering of the kerf.
- Burr formation on the exit side of the kerf.
Process Capabilities

- Process variables
  - Pressure
  - Nozzle diameter
  - Standoff distance
  - Abrasive type and grit number
  - Workpiece feed rate

- An abrasive water jet cuts through 356.6 mm thick slabs of concrete or 76.6-mm-thick tool steel plates at 38 mm/min in a single pass.

- Surface roughness ranges between 3.8 and 6.4 μm.

- Tolerance - ± 0.13 mm.

- Repeatability - ± 0.04 mm.

- Straightness – 0.05 mm per axis length.
Foundry sands are frequently used as abrasives.

However, garnet (the most common abrasive material) is 30 percent more effective than sand.

Cutting rate during machining of glass – 16.4 mm³/min.

This is 4 to 6 times higher for metals.

Surface roughness depends on the workpiece material, grit size, and type of abrasives.

A material with a high removal rate produces large surface roughness.
Fine grains are used for machining soft metals to achieve better roughness.

The decrease in surface roughness by using smaller grain size is related to the reduced depth of cut and the undeformed chip cross section.

A carrier liquid consisting of water with anticorrosive additives has higher density and contributes to higher acceleration of the grains.

This results in higher grain speed and increased metal removal rate.

Moreover, the carrier liquid spreads over the surface filling its cavities and forming a film that impedes the striking action of the grains.

Therefore, peaks in the surface irregularities are the first to be affected and the surface quality improves.
Thank you