Module
9
Non conventional Machining

Lesson
37
Water Jet and Abrasive Water Jet Machining

Instructional Objectives

- List four different non conventional machining processes
- Differentiate between water and abrasive water jet machining
- List different WJM and AWJM systems
- List ten different modules of AWJM systems
- List four applications of AWJM
- List three advantages of AWJM
- List materials that can be processed by AWJM
- Mention functions of different elements of AWJM
- Identify mechanism of material removal
- Develop models for mechanism of material removal
- Identify parameters related to product quality
- Identify five limitations of AWJM
- Identify environmental issues in the area of AWJM

Introduction

Water Jet Machining (WJM) and Abrasive Water Jet Machining (AWJM) are two non-traditional or non-conventional machining processes. They belong to mechanical group of non-conventional processes like Ultrasonic Machining (USM) and Abrasive Jet Machining (AJM). In these processes (WJM and AJWM), the mechanical energy of water and abrasive phases are used to achieve material removal or machining. The general grouping of some of the typical non-traditional processes are shown below:

- Mechanical Processes
  - USM
  - AJM
  - WJM and AWJM
- Thermal Processes
  - EBM
  - LBM
  - PAM
  - EDM and WEDM
- Electrical Processes
  - ECM
  - EDG
  - EJD
- Chemical Processes
  - Chemical milling
  - Photo chemical machining

WJM and AWJM can be achieved using different approaches and methodologies as enumerated below:

- WJM - Pure
- WJM - with stabilizer
- AWJM – entrained – three phase – abrasive, water and air
- AWJM – suspended – two phase – abrasive and water

- Direct pumping
- Indirect pumping
- Bypass pumping

However in all variants of the processes, the basic methodology remains the same. Water is pumped at a sufficiently high pressure, 200-400 MPa (2000-4000 bar) using intensifier technology. An intensifier works on the simple principle of pressure amplification using hydraulic cylinders of different cross-sections as used in "**Jute Bell Presses**". When water at such pressure is issued through a suitable orifice (generally of 0.2- 0.4 mm dia), the potential energy of water is converted into kinetic energy, yielding a high velocity jet (1000 m/s). Such high velocity water jet can machine thin sheets/foils of aluminium, leather, textile, frozen food etc.

In pure WJM, commercially pure water (tap water) is used for machining purpose. However as the high velocity water jet is discharged from the orifice, the jet tends to entrain atmospheric air and flares out decreasing its cutting ability.

Hence, quite often stabilisers (long chain polymers) that hinder the fragmentation of water jet are added to the water.

In AWJM, abrasive particles like sand (SiO_2), glass beads are added to the water jet to enhance its cutting ability by many folds. AWJ are mainly of two types – entrained and suspended type as mentioned earlier. In entrained type AWJM, the abrasive particles are allowed to entrain in water jet to form abrasive water jet with significant velocity of 800 m/s. Such high velocity abrasive jet can machine almost any material. Fig. 1 shows the photographic view of a commercial CNC water jet machining system along with close-up view of the cutting head.

Fig. 1 *Commercial CNC water jet machining system and cutting heads (Photograph Courtesy – Omax Corporation, USA)*

Application

The applications and materials, which are generally machined using WJ and AWJ, are given below:

Application

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

Materials

- Steels
- Non-ferrous alloys
- Ti alloys, Ni- alloys
- Polymers
- Honeycombs
- Metal Matrix Composite
- Ceramic Matrix Composite
- Concrete
- Stone – Granite
- Wood
- Reinforced plastics
- Metal Polymer Laminates
- Glass Fibre Metal Laminates

The cutting ability of water jet machining 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.

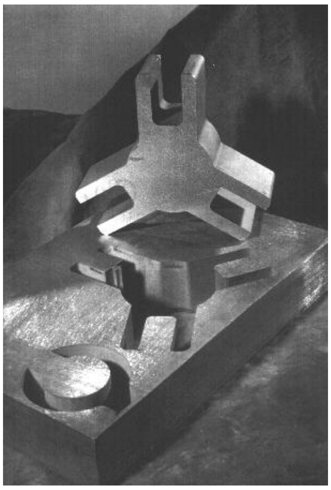

Fig. 2 *Stainless steel plate (50 mm thick) machined with AWJ*
(Photograph Courtesy – Omax Corporation, USA)

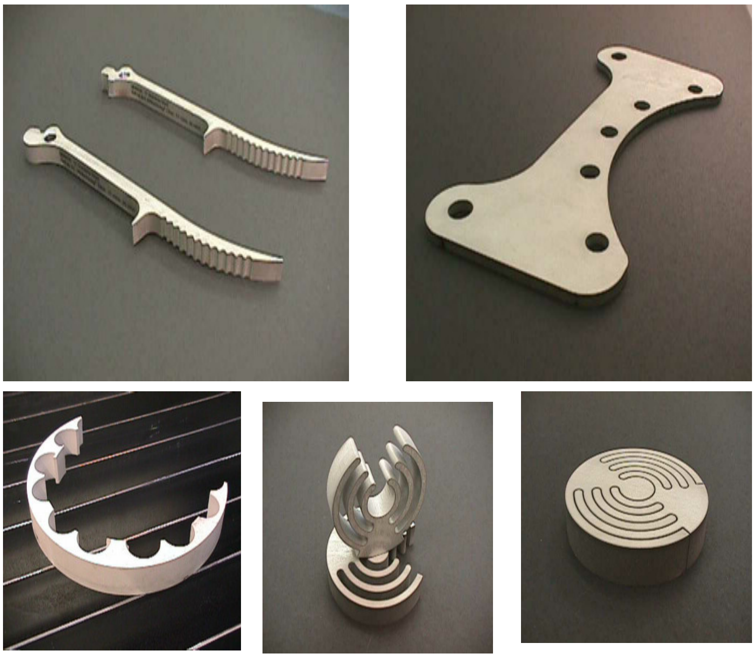

Fig. 3 *Different engineering components machined with AWJ*
(Photograph Courtesy – Omax Corporation, USA)

Fig. 2 depicts a typical example of AWJM, where 50 mm thick stainless steel has been machined. Fig. 3 shows the obtainable accuracy and precision with AWJM. Some of the job shop industries and manufacturers claim to have successfully used AWJM in free form surface generation by milling as shown in the following web page:

WJM and AWJM have certain advantageous characteristics, which helped to achieve significant penetration into manufacturing industries.

- 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
- Machine thick plates

Machine

Any standard abrasive water jet machining (AWJM) system using entrained AWJM methodology consists of following modules.

- LP booster pump
- Hydraulic unit
- Additive Mixer
- Intensifier
- Accumulator
- Flexible high pressure transmission line
- On-off valve
- Orifice
- Mixing Chamber
- Focussing tube or inserts
- Catcher
- CNC table
- Abrasive metering device
- Catcher

1. **LP Booster**
2. **Hydraulic drive**
3. **Additive mixer**
4. **Direction control**
5. **Intensifier**

5A.LP Intensifier
5B.HP Intensifier

6. **Accumulator**

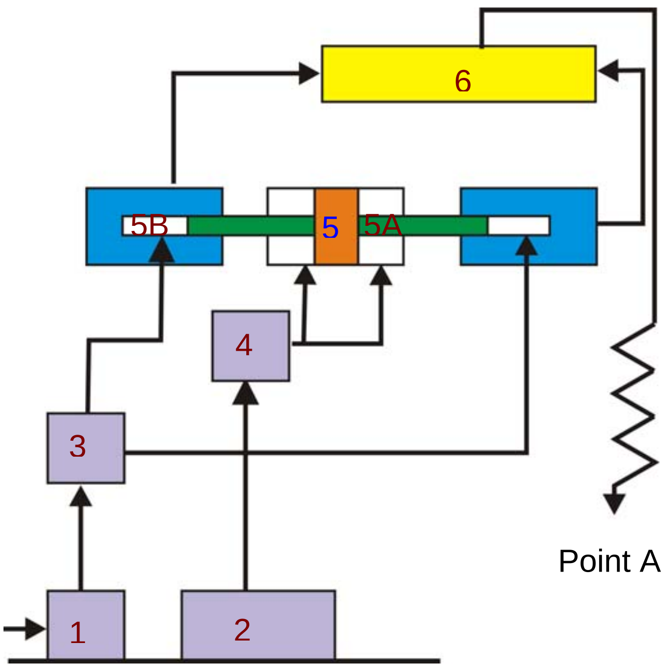

Fig. 4 *Schematic set-up of AWJM*

Intensifier, shown in Fig. 5 is driven by a hydraulic power pack. The heart of the 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.

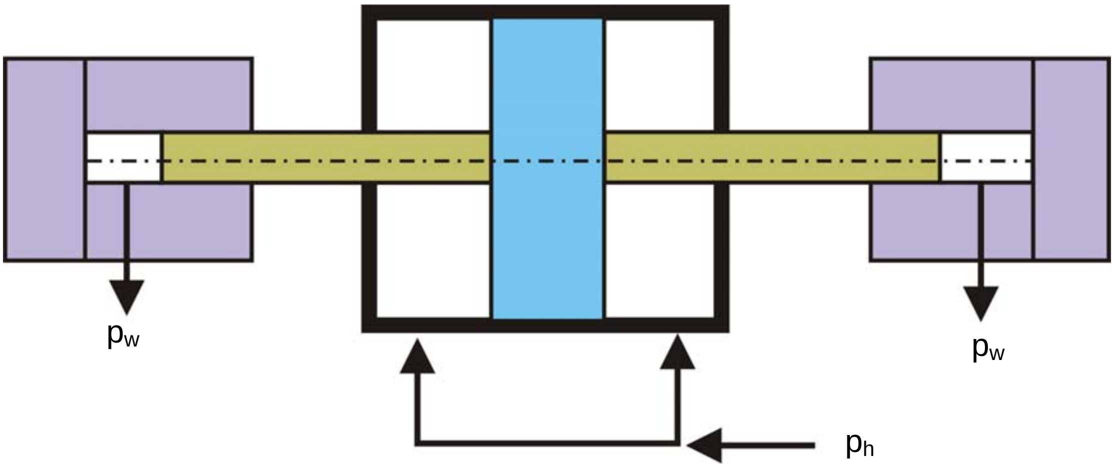

Fig. 5 *Intensifier – Schematic*

The hydraulic power pack delivers the hydraulic oil to the intensifier at a pressure of p_h . The ratio of cross-section of the two cylinders in the intensifier is say $\boldsymbol{A_{ratio}\ (A = A_{large} / A_{small})}$. Thus, pressure amplification would take place at the small cylinder as follows.

$$p_h \times A_{large} = p_w \times A_{small}$$

$$p_w = p_h \times \frac{A_{large}}{A_{small}}$$

$$p_w = p_h \times A_{ratio}$$

Thus, if the hydraulic pressure is set as 100 bar and area ratio is 40, p_w = 100 x 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 supplying it to 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 (refer Fig. 6). 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

High-pressure water is then fed through the flexible stainless steel pipes to the cutting head. It is worth mentioning here that such pipes are to carry water at 4000 bar (400 MPa) with flexibility incorporated in them with joints but without any leakage. Cutting head consists of orifice, mixing chamber and focussing tube or insert where water jet is formed and mixed with abrasive particles to form abrasive water jet.

Fig. 6 shows a cutting head or jet former both schematically and photographically. 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.

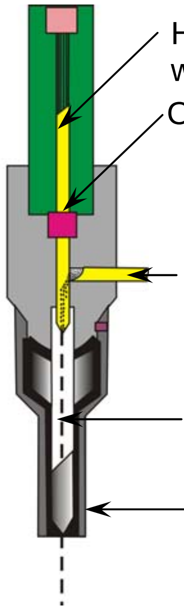

Fig. 6 *Schematic and photographic view of the cutting head (Photograph Courtesy – Omax Corporation, USA)*

The potential or pressure head of the water is converted into velocity head by allowing the high-pressure water to issue 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 is the water pressure and ρ_w is the density of water. 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. The mixing chamber has a typical dimension of 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. The reader may consult standard literature on transportation of powders.

Mixing

Fig. 7 schematically shows the mixing process. Mixing means gradual entrainment of abrasive particles within the water jet and finally the abrasive water jet comes out of the focussing tube or the nozzle.

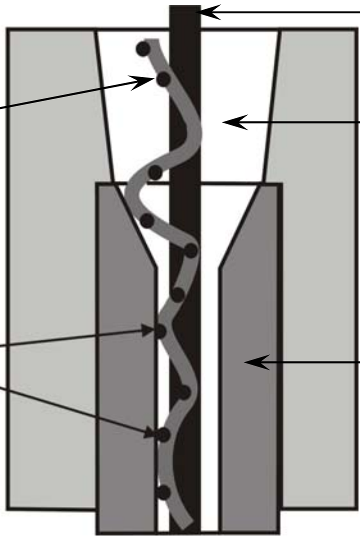

Fig. 7 *Schematic view of mixing process*

During mixing process, the abrasive particles are gradually accelerated due to transfer of momentum from the water phase to abrasive phase and when the jet finally leaves the focussing tube, both phases, water and abrasive, are assumed to be at same velocity.

The mixing chamber, as shown in Fig. 7 and Fig. 8, is immediately followed by the focussing tube or the inserts. The focussing tube is generally made of tungsten carbide (powder metallurgy product) having an 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.

Mixing process may be mathematically modelled as follows. Taking into account the energy loss during water jet formation at the orifice, the water jet velocity may be given as,

$$v_{wj} = \Psi \sqrt{\frac{2 p_w}{\rho_w}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

where,

Ψ = Velocity coefficient of the orifice

The volume flow rate of water may be expressed as

$$\dot{q}_w = \phi \times v_{wj} \times A_{orifice}$$

$$\dot{q}_w = \phi \times v_{wj} \times \frac{\Pi}{4} d_o^{\,2}$$

$$\dot{q}_w = \phi \times \frac{\Pi}{4} d_o^{\,2} \times \Psi \sqrt{\frac{2 p_w}{\rho_w}}$$

$$\dot{q}_w = c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2 p_w}{\rho_w}}$$

where,

ϕ = Coefficient of "vena-contracta"
c_d = Discharge coefficient of the orifice

Thus, the total power of the water jet can be given as

$$P_{wj} = p_w \times q_w$$

$$P_{wj} = p_w \times c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2 p_w}{\rho_w}}$$

$$P_{wj} = c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2 p_w^{\,3}}{\rho_w}}$$

During mixing process as has been discussed both momentum and energy are not conserved due to losses that occur during mixing. But initially it would be assumed that no losses take place in momentum, i.e., momentum of the jet before and after mixing is conserved.

$$\sum \left(\dot{m} v \right)_{before} = \sum \left(\dot{m} v \right)_{after}$$

$$\left(\dot{m}_{air} v_{air} + \dot{m}_w v_{wj} + \dot{m}_{abr} v_{abr} \right)_{before} = \left(\dot{m}_{air} v_{air} + \dot{m}_w v_{wj} + \dot{m}_{abr} v_{abr} \right)_{after}$$

The momentum of air before and after mixing will be neglected due to very low density. Further, it is assumed that after mixing both water and abrasive phases attain the same velocity of v_{wj}. Moreover, when the abrasive particles are fed into the water jet through the port of the mixing chamber, their velocity is also very low and their momentum can be neglected.

$$\therefore \dot{m}_w v_{wj} = \left(\dot{m}_w + \dot{m}_{abr}\right) v_{awj}$$

$$v_{awj} = \frac{\dot{m}_w}{\left(\dot{m}_w + \dot{m}_{abr}\right)} v_{wj}$$

$$v_{awj} = \frac{1}{\left(1 + R\right)} v_{wj}$$

where,

$$R = \text{loading factor} = \frac{\dot{m}_{abr}}{\dot{m}_w}$$

As during mixing process momentum loss occurs as the abrasives collide with the water jet and at the inner wall of the focussing tube multiple times before being entrained, velocity of abrasive water jet is given as,

$$v_{awj} = \eta \frac{1}{\left(1 + R\right)} v_{wj}$$

where, η = momentum loss factor.

Suspension Jet

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

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 as already given in Table. 2. Fig. 8 shows the working principle of indirect and Bypass pumping system of suspension AWJM system.

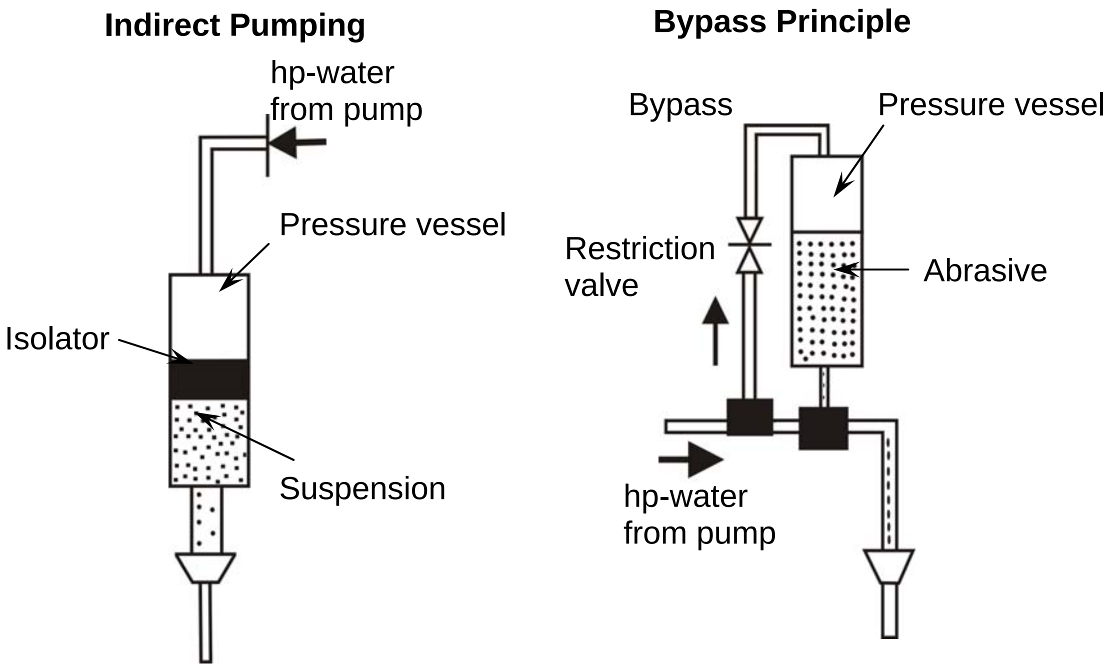

Fig. 8
Schematic of AWJM (Suspension type)

In suspension AWJM, preformed mixture of water and abrasive particles is pumped to a sufficiently high pressure and store in pressure vessel. Then the premixed high-pressure water and abrasive is allowed to discharge from a nozzle to form abrasive water jet.

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. Fig. 9 shows three different types of catcher – water basin type, submerged steel balls and TiB_2 plate type.

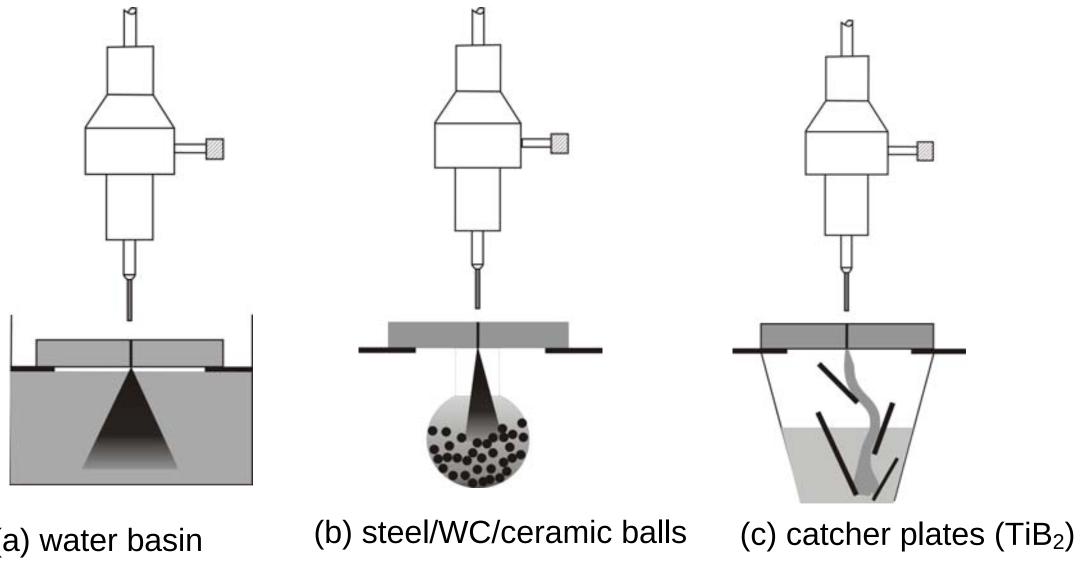

Fig. 9 *Some typical catchers*

Moreover the catcher can be of pocket type or line type. In pocket type, the catcher basin travels along the jet. In line type, the catcher basin only travels along one axis of the CNC table and its length covers the width of the other axis of the CNC table.

Mechanism of material removal

The general domain of parameters in entrained type AWJ machining system is given below:

- 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 - 0.1 to 1.0 Kg/min
- Stand off distance – 1 to 2 mm
- Machine Impact Angle – 60^o to 90^0
- Traverse Speed – 100 mm/min to 5 m/min
- Depth of Cut – 1 mm to 250 mm

Mechanism of material removal in machining with water jet and abrasive water jet is rather complex. In AWJM of ductile materials, material is mainly removed by low angle impact by abrasive particles leading to ploughing and micro cutting. Such process has been studied in detail initially by Finnie[1] as available in the edited volume by Engels[1]. Further at higher angle of impact, the material removal involves plastic failure of the material at the sight of impact, which was studied initially by Bitter[2,3]. Hashish[4] unified such models as applicable under AWJM at a later stage. In case of AWJM of brittle materials, other than the above two models, material would be removed due to crack initiation and propagation because of brittle failure of the material. Kim et al [5] have studied this in detail in the context of AWJM.

In water jet machining, the material removal rate may be assumed to be proportional to the power of the water jet.

$$MRR \propto P_{wj} \propto c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2 p_w^{\,3}}{\rho_w}}$$

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

The proportionality constant *u* is the specific energy requirement and would be a property of the work material.

Fig. 10, Fig. 11, Fig. 12 and Fig. 13 show the cut generated by an AWJM in different sections. It is called a kerf.

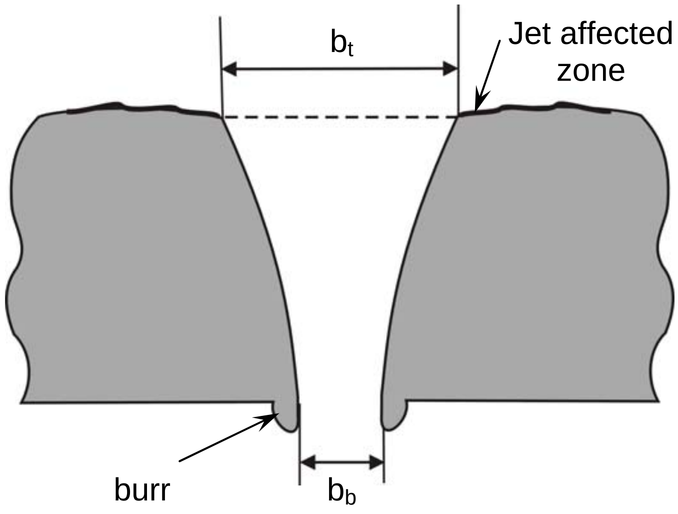

Fig. 10 *Schematic of AWJM kerf*

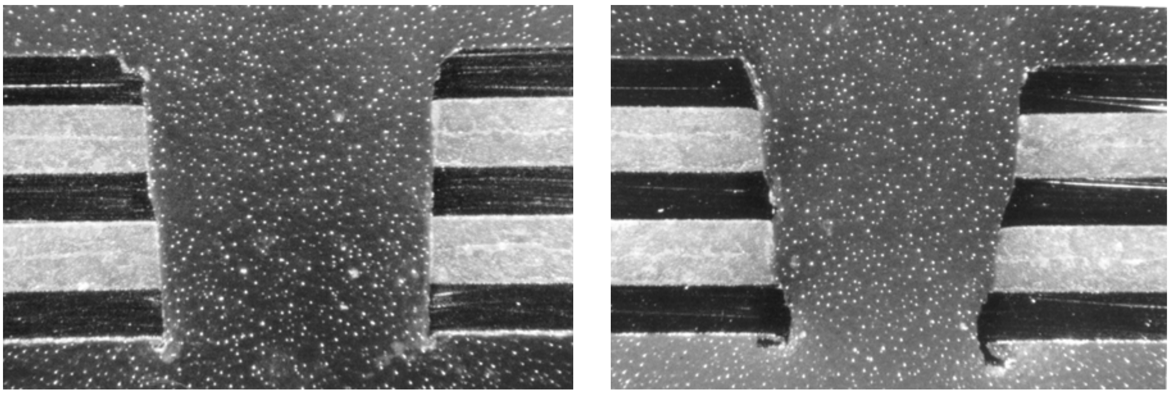

Fig. 11 *Photographic view of kerf (cross section)*

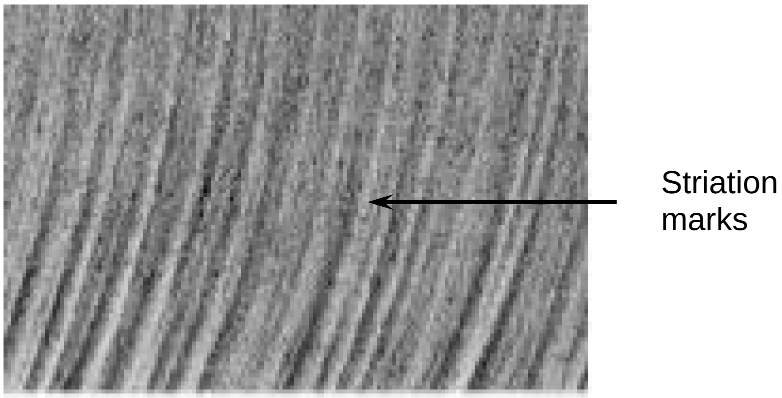

Fig. 12 *Photographic view of kerf (longitudinal section)*

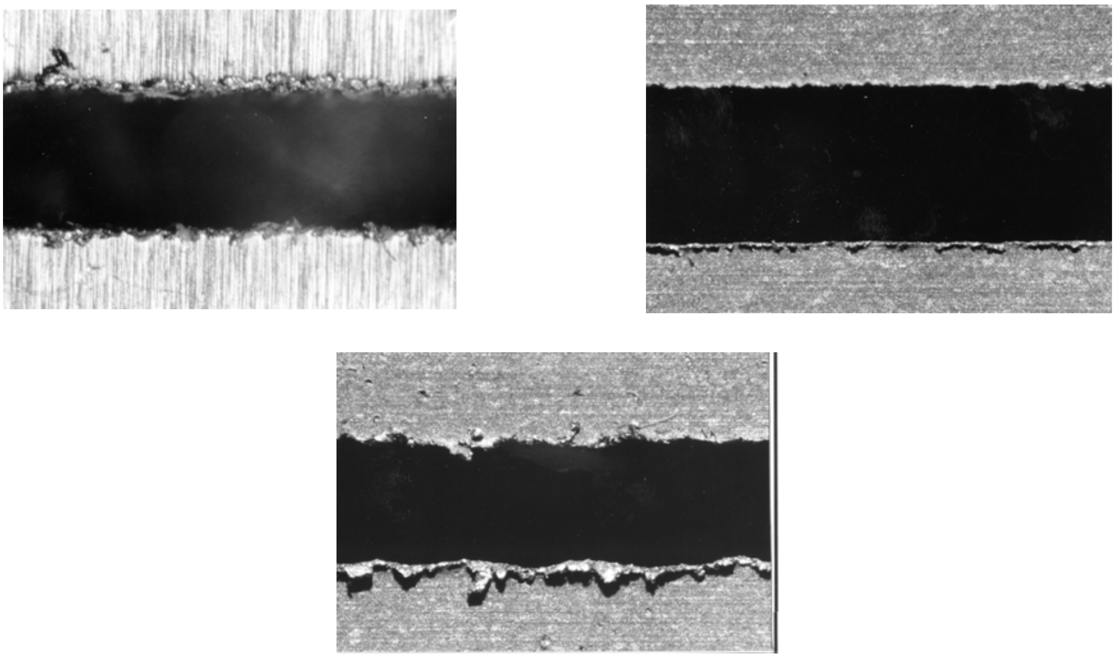

Fig. 13 *Photographic view of the kerf (back side)*

The top of the kerf is wider than the bottom of the kerf. Generally the top width of the kerf is equal to the diameter of the AWJ. Once again, diameter of the AWJ is equal to the diameter of the focussing tube or the insert if the stand-off distance is around 1 to 5mm. The taper angle of the kerf can be reduced by increasing the cutting ability of the AWJ. Fig. 12 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 of the kerf, the material removal is by low angle impact of the abrasive particle; where as at the bottom of the kerf it is by plastic failure. Striation formation occurs due to repeated plastic failure.

Fig. 13 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

Models proposed by Finnie, Bitter, Hashish and Kim though are very comprehensive and provide insight into the mechanism of material removal, require substantial information on different aspects and parameters which may not be readily available.

Thus a more workable, simple but reliable model for predicting depth of penetration as proposed by the group working in TU Delft, the Netherlands is being presented here.

The power of the abrasive phase of the abrasive water jet can be estimated as,

$$P_{abr} = \frac{1}{2}\dot{m}_{abr}\, v_{awj}^2$$

$$P_{abr} = \frac{1}{2}\dot{m}_{abr}\left\{\eta \frac{1}{\left(1+R\right)} v_{wj}\right\}^2$$

$$P_{abr} = \frac{1}{2}\dot{m}_{w}\, R\left\{\eta \frac{1}{\left(1+R\right)} v_{wj}\right\}^2$$

$$P_{abr} = \frac{1}{2}c_d \times \frac{\Pi}{4} d_o{}^2 \rho_w v_{wj} R\eta^2 \left(\frac{1}{1+R}\right)^2 v_{wj}^2$$

$$P_{abr} = c_d \times \frac{\Pi}{8} d_o{}^2 \rho_w R\eta^2 \left(\frac{1}{1+R}\right)^2 v_{wj}^3$$

$$P_{abr} = c_d \times \frac{\Pi}{8} d_o{}^2 \rho_w R\eta^2 \left(\frac{1}{1+R}\right)^2 \left(\frac{2p_w}{\rho_w}\right)^{3/2}$$

$$P_{abr} = c_d \times \frac{\sqrt{2}\Pi}{4} d_o{}^2 R\eta^2 \left(\frac{1}{1+R}\right)^2 \frac{p_w^{3/2}}{\rho_w^{1/2}}$$

$$P_{abr} = c_d \times \frac{\Pi}{4} d_o{}^2 R\left(\frac{\eta}{1+R}\right)^2 p_w^{3/2} \sqrt{\frac{2}{\rho_w}}$$

Thus it may be assumed that the material removal rate is proportional to the power of abrasive phase of AWJ. The water phase does not contribute to material removal in AWJM.

$$MRR = \dot{Q} = \frac{P_{abr}}{u_{job}}$$

where,

u_{job} = specific energy requirement in machining a material in AWJM

Now

$MRR = h_t w v_f$

Where,

h_t = depth of penetration

w = width of the kerf
= $(w_{top} + w_{bottom}) / 2$
$\approx d_i$, the diameter of the focussing tube or nozzle or the insert

v_f = traverse speed of the AWJ or cutting speed

Therefore,

$MRR = h_t d_i v_f$

$$\therefore h_t = c_d \times \frac{\Pi}{4} d_o{}^2 R \left(\frac{\eta}{1+R} \right)^2 \frac{p_w^{3/2}}{u_{job} d_i v_f} \sqrt{\frac{2}{\rho_w}}$$

Generally,

$$MRR = \xi \frac{P_{abr}}{u_{job}}$$

where, ξ is a coefficient, which takes into account several factors like sharpness or dullness of the abrasive, friability of the abrasives, stand-off distance, process inhomogenities etc

Therefore,

$$\therefore h_t = \xi c_d \times \frac{\Pi}{4} d_o{}^2 R \left(\frac{\eta}{1+R} \right)^2 \frac{p_w^{3/2}}{u_{job} d_i v_f} \sqrt{\frac{2}{\rho_w}}$$

Now the manufacturing strategy should be selected in such a way so that maximization of h_t takes place.

$R = \frac{\dot{m}_{abr}}{m_w}$, is the loading parameter .

Optimal loading ratio is required to be determined by differentiating with respect to the loading ratio, *R*

$$h_t = \overline{K} \frac{R^2}{(1+R)^2}$$

Where, $\overline{K}$ is the constant.

$$\frac{\partial h_t}{\partial R} = \overline{K}(1+R)^2 - 2R - 2(1+R).R^2 = 0$$

$$(1+R) - 2R = 0$$

$$1 - R = 0 \Rightarrow R = 1$$

Thus, theoretically maximum depth of penetration occurs at R = 1. The variation in h_t with R is shown in Fig. 14.However, in practice maximum h_t is obtained at R = 0.5 to 0.6 for all other parameters remaining same. Fig. 15 also provides some indications to increase depth of cut.

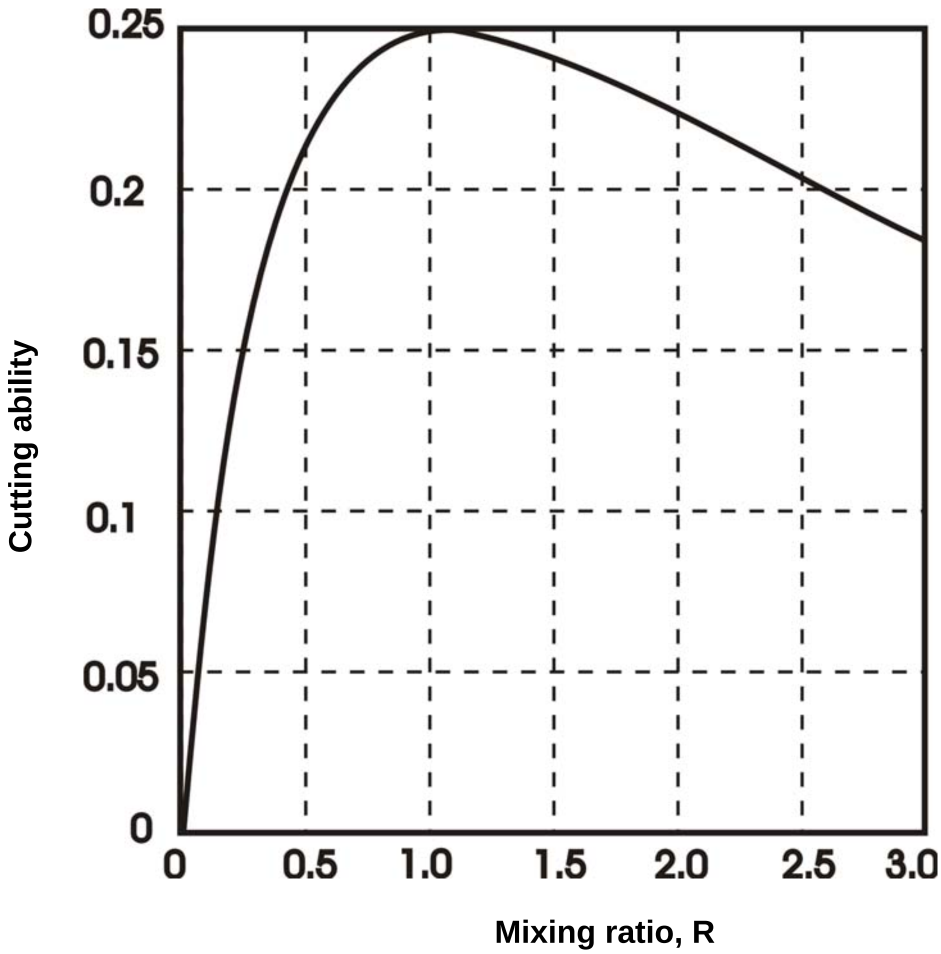

Fig. 14 *Variation in cutting ability of AWJM with mixing ratio*

Environmental issues and future

Nowadays, every manufacturing process is being re-evaluated in terms of its impact on the environment. For example, use of conventional coolants in machining and grinding is being looked upon critically from the point of view of its impact on environment. The environmental issues relevant to AWJM are,

- water recycling
- spent water disposal
- chip recovery
- abrasive recovery and reuse

Environmental issues and concerns have lead the researchers to use such mediums and abrasives that do not require disposal, recycling or lead to pollution. Work is going on in the area of high-pressure cryogenic jet machining (Fig. 16) where liquid nitrogen replaces the water phase and dry ice crystals (solid CO_2 crystals) replace the abrasive

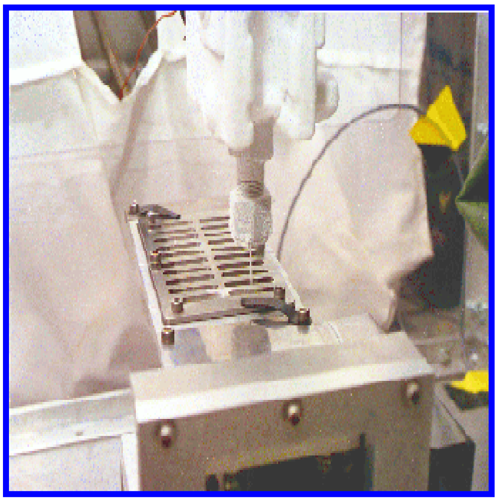

Fig. 15 *Cryogenic Abrasive Jet Machining*

phase leading to no need of disposal or waste generation. The removed work material in the form of microchips can be collected much easily reducing the chances of environmental degradation.

Problems

1. Assuming no losses, determine water jet velocity, when the water pressure is 4000 bar, being issued from an orifice of diameter 0.3 mm

Ans:

$$v_w = \sqrt{\frac{2p}{\rho_w}} = \sqrt{\frac{2x4000x10^5}{1000}} = 894 m/s$$

2. Determine the mass flow rate of water for the given problem assuming all related coefficients to be 1.

Ans:

$$m_w = \rho_w.Q_w = \rho_w \frac{\pi}{4} d_o^2 v_w$$

$$= 1000x\frac{\pi}{4}x(0.3x10^{-3})^2 x894$$

$$= 0.0631 \quad kg/s$$

$$= 0.0631x60 = 3.79 \quad kg/\min$$

3. If the mass flow rate of abrasive is 1 kg/min, determine the abrasive water jet velocity assuming no loss during mixing process using the above data (data of Question. 1, 2 and 3)

Ans:

$$v_{awj} = \left(\frac{1}{1+R}\right) v_{wj} = \left(\frac{1}{1+\frac{m_{abr}}{m_w}}\right) v_{wj} = \left(\frac{1}{1+\frac{1}{3.79}}\right) x894 = 707 m/s$$

4. Determine depth of penetration, if a steel plate is AWJ machined at a traverse speed of 300 mm/min with an insert diameter of 1 mm. The specific energy of steel is 13.6 J/mm^3.

Ans:

$$h_t = \frac{\pi}{4} d_o^2 R \left(\frac{1}{1+R}\right)^2 \frac{p^{3/2}}{u_{job} d_i V_f} \sqrt{\frac{2}{\rho_w}}$$

$$h_t = \frac{\pi}{4}(0.3x10^{-3})^2 \frac{1}{3.8}\left(\frac{1}{1+\frac{1}{3.8}}\right)^2 \frac{\left(4000x10^5\right)^{3/2}}{13.6x10^9 x1x10^{-3} x\frac{300}{60} x10^{-3}} \sqrt{\frac{2}{1000}}$$

$$h_t = 77.6 \quad mm$$

Quiz Questions

1. WJM cannot be used to machine

   (a) frozen food
   (b) plywood
   (c) leather
   (d) steel plates ANSWER (d)

2. In AWJM mixing process takes place in

   (a) intensifier
   (b) catcher
   (c) mixing chamber
   (d) orifice ANSWER (c)

3. Abrasive water jet velocity increases with (keeping all other parameters unchanged)

   (a) increasing traverse velocity of the job
   (b) decreasing mass flow rate of abrasive
   (c) decreasing traverse velocity of the job
   (d) increasing mass flow rate of abrasive
   ANSWER (b)

4. In an environment friendly development concerning AWJM, the following is used as abrasive

   (a) dry ice
   (b) cubic boron nitrite
   (c) diamond
   (d) tungsten carbide ANSWER (a)

<u>Test Items</u>

1. List different modules of AWJM systems

Ans:

- LP booster pump
- Hydraulic unit
- Additive Mixer
- Intensifier
- Accumulator
- Flexible high pressure transmission line
- On-off valve
- Orifice
- Mixing Chamber
- Focussing tube or inserts
- Catcher

- CNC table
- Abrasive metering device
- Catcher

2. List different WJM and AWJM systems

Ans:

- WJM - Pure
- WJM - with stabilizer
- AWJM – entrained – three phase – abrasive, water and air
- AWJM – suspended – two phase – abrasive and water
    - Direct pumping
    - Indirect pumping
    - Bypass pumping

3. Identify the limitations of AWJM from environmental issues

Ans:

- water recycling
- spent water disposal
- chip recovery
- abrasive recovery and reuse

4. List quality parameters associated with AWJM

Ans:

- striation formation
- surface finish of the kerf
- tapering of the kerf
- burr formation on the exit side of the kerf

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