

**2009 American WJTA Conference and Expo
August 18-20, 2009 • Houston, Texas**

Paper

SPECIAL AWJ NOZZLES

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ABSTRACT

This paper presents data on using special nozzles for special applications. A relatively large power AWJ nozzle was built to cut relatively thick materials. In this nozzle, a segmented mixing tube was used to form mixing tubes up to 1-m long. Micro AWJ nozzles were also built to fire 25 micron waterjets in 180-micron diameter mixing tubes at 690 MPa. This was used to cut thin kerfs in metal. A small profile (~ 30-mm) AWJ nozzle was built for cutting in small spaces such as inside of an I-beam. A deep kerf nozzle with capability of feeding into the kerf is also discussed. The above nozzles and the associated applications will be described along with the used parameters and the obtained results.

1. INTRODUCTION

In Abrasive–waterjet (AWJ) nozzles, the potential pressure energy is converted to waterjet kinetic energy. This energy is then used to accelerate abrasives who become the cutting agents when striking a workpiece. This energy transformation and exchange occurs in a field whose geometry affects the resulting jet and its cutting effectiveness. It has been typical that an AWJ geometry is optimized based on the parameters to be used. However, in some situations, the geometry is mandated by the application and thus the parameters are selected to best cut the material.

An AWJ consists of several components whose design may be significantly different from one application to another. The following is a list of critical components and geometries which may have significantly different geometries from one application to another:

- Ultra High Pressure (UHP) water tube: This UHP tube provides the high-pressure water to the orifice. Its diameter and settling length are important parameters.
- Orifices: The orifice is the device that converts the potential energy to kinetic energy. The orifice shape and edge geometry affect jet coherency which in turn affect the performance of an AWJ.
- Abrasive receiving (mixing) chamber: The waterjet exits the orifice to the receiving (mixing) chamber where abrasives are also fed. The geometry of this chamber is of great importance for reliable AWJ performance.
- Mixing tube: In the mixing tube, momentum transfer occurs from the waterjet to the abrasive particles. Its length and diameter are the critical parameters. Performance.
- Ports: An AWJ may have several ports whose size and location are of importance. Among these are abrasive feed and vacuum assist ports.

In addition to the above components, an AWJ nozzle may be closely connected to an on/off valve which may have an effect on the AWJ operation. Figure 1 shows a typical AWJ nozzle showing the above components. The typical size range for the most common nozzles in the industry is listed below:

- | | |
|--|-------------------|
| • Water body inside diameter | ~ 6mm |
| • Water body length | ~ 75 mm |
| • Distance from orifice to mixing tube | ~ 20 mm |
| • Mixing chamber length | ~ 10 mm – 20 mm |
| • Mixing chamber diameter/shape | ~ 7 mm |
| • Mixing tube length | ~ 50 mm - 125 mm |
| • Mixing tube diameter | ~ 0.5 mm – 1.3 mm |

It can be loosely specified that the following two relationships apply to most commonly used AWJ nozzles:

- The mixing tube length to diameter ratio is about 3
- The mixing tube diameter to orifice diameter ratio is about 3

In addition to the above, some rough parameters selection rules are:

- The abrasive particle size should not exceed half the difference between mixing tube and orifice diameters
- The abrasive mass flow rate is about 10-15% of the water mass flow rate

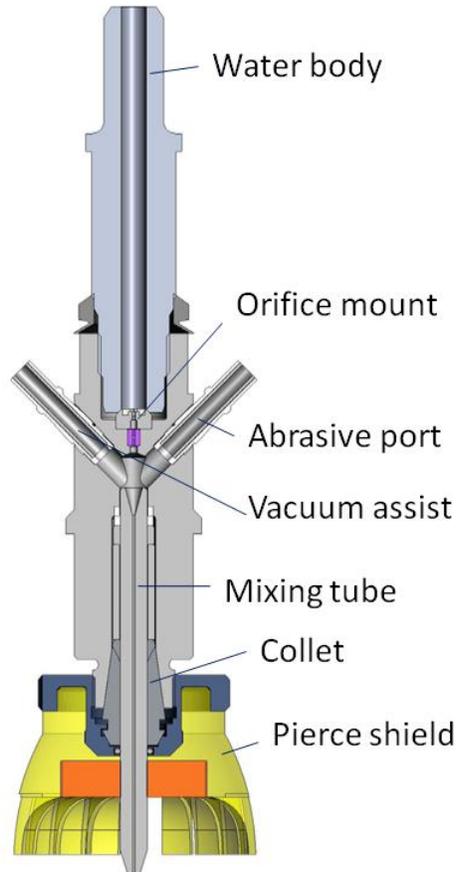


Figure 1: Typical AWJ Nozzle for Common Applications

In the following sections we present special nozzles with different ratios and parameters than the above mentioned, and discuss their uses. However, before this, we present general equations for calculating the abrasive particle velocity and the factors that affect AWJ efficiency.

2. ABRASIVE PARTICLE VELOCITY

A simple formula for the abrasive axial velocity distribution has been derived (1, 2) based on the momentum and continuity equations of the liquid and solid flow. The force F_p acting on a particle moving at a velocity V in the mixing tube is:

$$F_p = \frac{1}{2} \rho_o A_p (U - V)^2 \quad . \quad (1)$$

Newton's equation for particle motion can be written as:

$$F_p = m_p V \frac{\partial V}{\partial x} \quad . \quad (2)$$

The overall momentum balance equation at a location x from the entry of the mixing tube is:

$$\dot{m}_w V_j = \dot{m}_w U + \dot{m}_a V \quad . \quad (3)$$

The above equations can be solved to yield the following equation for the particle velocity V at a distance x :

$$x = \frac{1}{K} \left[\frac{\lambda}{\lambda - 1} - \ln \left(\frac{1}{1 - \lambda} \right) \right] \quad , \quad (4)$$

Where

$$K = \frac{3C_D(1+r)^2}{4S_a d_p} \quad (5)$$

When the jet breaks up into droplets and mixes with air, the virtual specific gravity of the mixture can be assumed to be equal to (d_n^2/d_m^2) instead of 1. This will mathematically alter S_a in the above equation by the same ratio. λ in the above equation is defined as:

$$\lambda = \frac{V}{V_{\max}} = \frac{V}{V_j/(1+r)} \quad (6)$$

Where $r = \dot{m}_a/\dot{m}_w$ is the abrasive loading ratio, and $V_{\max} = V_j/(1+r)$ is the maximum possible abrasive particle velocity. In the above equation, λ can be considered a mixing tube length factor that approaches unity as the mixing tube length approaches infinity. This is different from the momentum transfer efficiency, which expresses the ratio of the actual particle velocity V_a to the theoretical abrasive particle velocity V . Accordingly, if ζ is defined as the momentum transfer efficiency, then:

$$\zeta = \frac{V_a}{V} \quad (7)$$

Relating the actual abrasive particle velocity to the maximum theoretical particle velocity, V_{\max} defines an overall momentum transfer efficiency ζ_0 , which can be expressed as:

$$\zeta_0 = \zeta \lambda = \frac{V_a}{V_{\max}} = \frac{V_a}{V_j/(1+r)} \quad (8)$$

Table 1 shows the mixing tube length for different cases for a mixing tube length factor of 90%, i.e., $\lambda = 0.9$.

Table 1. Mixing Tube Length for $\lambda = 0.9$

Mesh No.	$r = \dot{m}_a / \dot{m}_w$	0.1	0.12	0.15	0.2	0.25
	d_p (mm)	Mixing tube length, l_m (mm)				
16	1.65	439	423	401	369	340
36	0.76	202	195	185	170	157
60	0.38	101	98	93	85	78
80	0.25	67	65	62	57	52
100	0.13	34	33	31	28	26

Observe that larger particles require longer mixing tubes; note also that as the abrasive flow rate increases, shorter tubes can be used to attain the maximum velocity. For the commonly used 100 mesh abrasives, for example, a mixing tube length of only 33 mm is required for an abrasive loading ratio of 0.12. The typical mixing tube length used in industry for this case, however, is about 76 mm. The additional length is used to collimate the jet and to raise the value of λ to about 0.95, as can be calculated from the above equations. Note that the additional 43 mm of mixing tube length contributes only 5% to the maximum possible velocity.

3. AWJ POWER EFFICIENCY

The AWJ power efficiency (2) is defined as the ratio of the kinetic power of the abrasive particles to that of the waterjet stream. The maximum possible power transmission efficiency is obtained when the momentum transfer efficiency is 100%.

The waterjet stream hydraulic power, E , is:

$$E = \frac{1}{2} \dot{m}_w V_j^2, \quad (9)$$

The abrasive kinetic power E_a can be calculated from:

$$E_a = \frac{1}{2} \dot{m}_a V_a^2, \quad (10)$$

Using $r = \dot{m}_a / \dot{m}_w$, and $V_a = \zeta_o V_j / (1 + r)$ from equation (8), the maximum possible power efficiency can be expressed as:

$$\eta = r \zeta_o^2 / (1 + r)^2, \quad (11)$$

From this equation, it can be determined that the maximum possible power efficiency of AWJ is 25% which occurs when $\zeta_o = 1$ and the loading ration $r = 1$, i.e. when the mixing tube is very long and the abrasive flow rate equals the water flow rate. This is not a practical condition for cutting with AWJ but may be for cleaning operations. The abrasive particle velocity at this theoretically

maximum efficiency condition is 50% of the waterjet velocity. At a practical loading ratio of 0.125, the maximum power efficiency is 9.88% and the maximum abrasive particle velocity is 89% of the waterjet velocity. Using a momentum transfer efficiency ξ_o of 90%, the AWJ power transmission efficiency is only 8%.

4. SPECIAL AWJ NOZZLES

4.1 Large Nozzle for Thick Material Cutting

To cut thick materials, high power and relatively large diameter jets are needed (3). This is due to the wall drag which reduces the momentum of the jet. This reduction in momentum reduces the penetration rate resulting in jet deflection and increased front edge kerf curvature. This is typically manifested at the bottom of the cut where the lag or trailback is most evident (3), see Figure 2. The larger the trailback the more difficult it is to produce geometrically-correct corners and tight curves at the bottom of the cut and also along the thickness of the material. While the trailback at a given depth can be eliminated by applying a lead angle during cutting (3), the front leading edge bow cannot easily be compensated for. This requires controlling the jet structure.

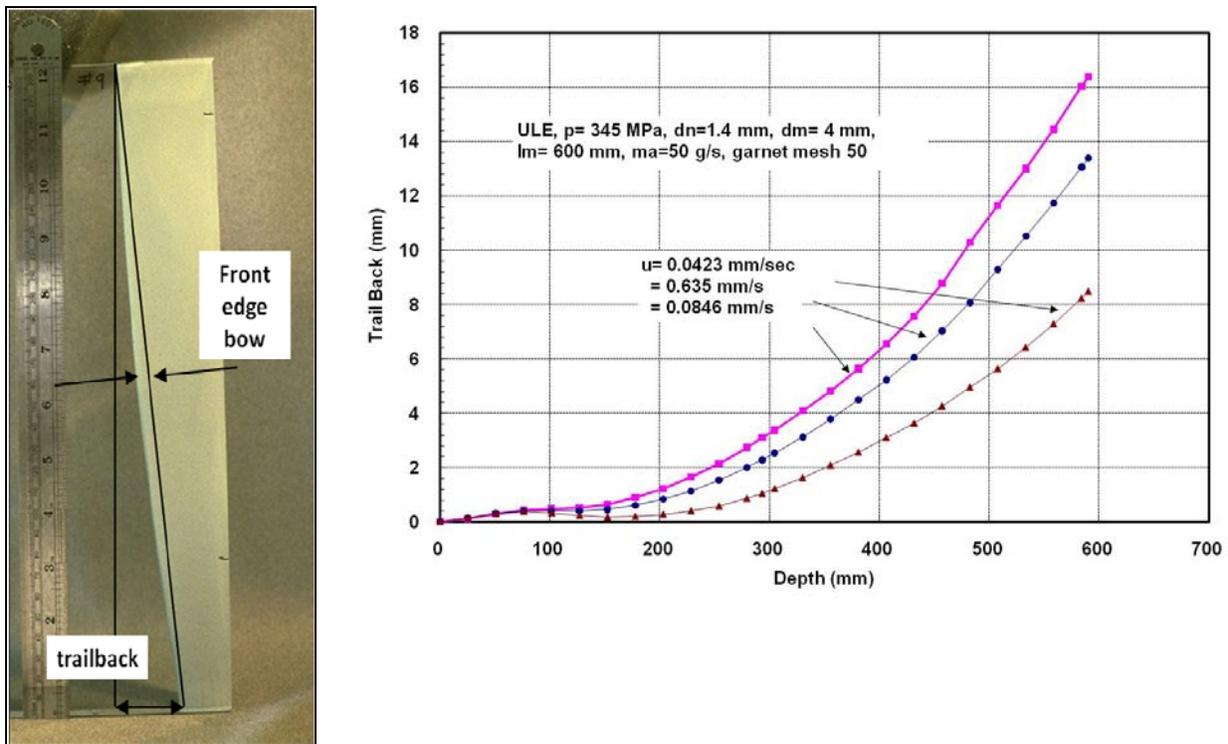
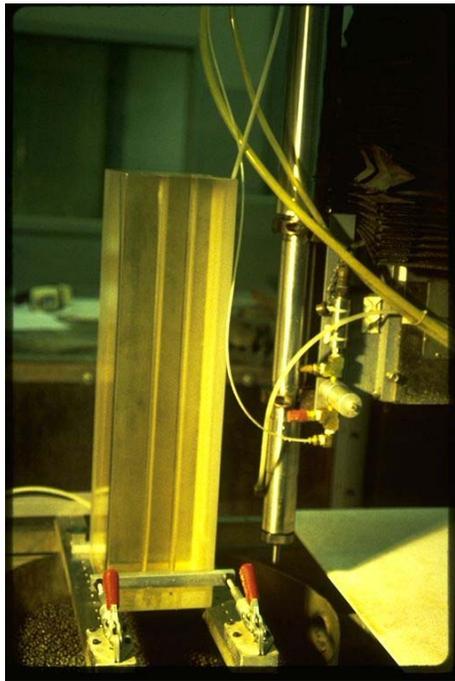


Figure 2: An AWJ Cut in 300-mm Thick Glass Showing Trailback and Front Edge Bow

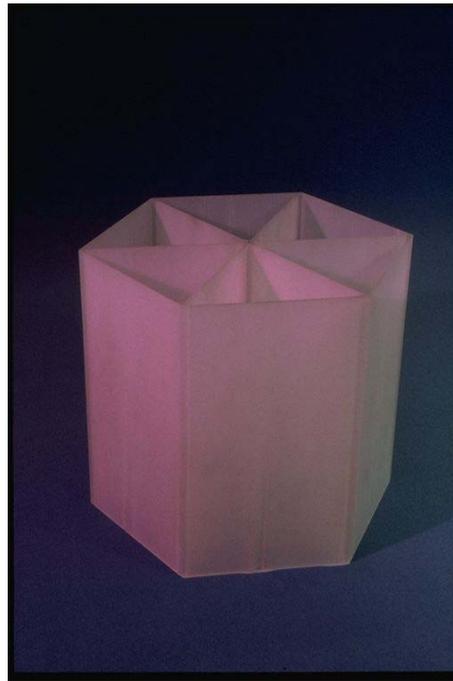
It was required to cut thick glass sections up to 300-mm thick to produce accurate honeycomb structures with relatively thin struts (2 mm with no more than 0.25mm deviation top to bottom). Corners were in the order of 6-mm radius. This requirement resulted in the development of a special nozzle to meet these requirements and also to be productive (~0.2 mm/s speed). The following are some features of this nozzle.

- Water body inside diameter ~ 11 mm
- Waterjet orifice size ~ 1 mm
- Water body length ~ 300 mm
- Mixing tube length ~ 600mm - 900 mm
- Mixing tube diameter ~ 4 mm

Figure 3a shows this nozzle on the left side next to a 600 mm thick glass block. Figure 3b shows a precise glass isogrid part cut with this nozzle. Figure 3c shows a compound AWJ nozzle.



a- 900-mm Long Mixing Tube



b-Glass Part Cut with a Large AWJ Nozzle



c- Compound Mixing Tub AWJ Nozzle

Figure 3: Pictures of Large Nozzles and a Cut Glass Sample

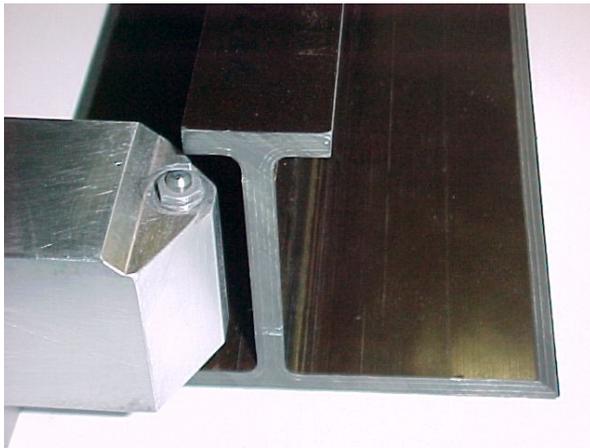
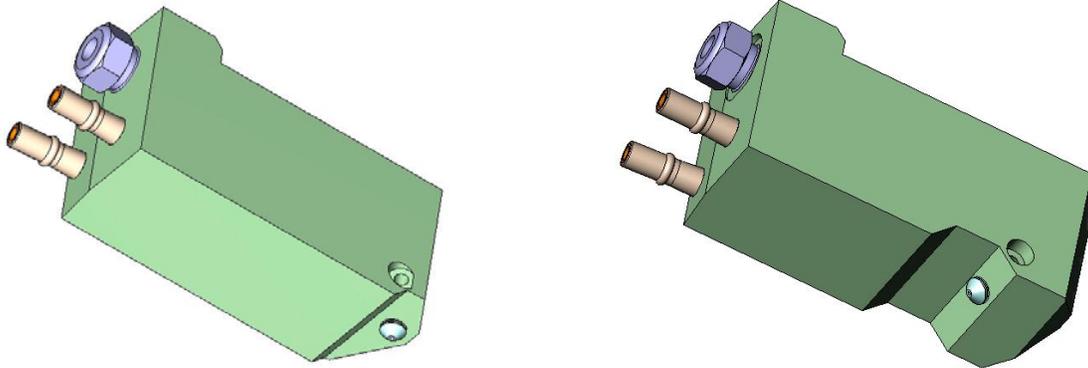
4.2 Sidfire Nozzle

Cutting in tight spaces with conventional AWJ nozzles may not be possible because of the dimensional requirements of the different components. For example, using a mixing tube length of 100-mm may not allow the nozzle to enter a space of only 50-mm height. Also, sometimes cutting from one side of the surface may not be possible because the other side may have areas that can be affected by the exiting jet.

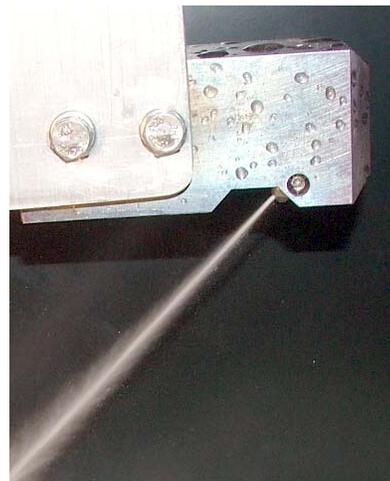
The sidfire nozzle was developed for the above situations but more specifically for cutting composite aircraft stringers. The flanges of the stringers need to be trimmed, cut to the required

shape and also beveled. Figure 4 shows a typical wing stringer cross-sectional geometry for the 787 aircraft wing with a sidefire nozzle next to it.

There are several challenges to the sidefire nozzle. First, the upstream flow passage for the high pressure water is not conducive to forming a coherent waterjet. The sharp change in the flow direction will cause turbulence and pressure loss. Second, the mixing tube is significantly shorter than the ideal or common length (~100 diameters). A typical length to diameter ratio of a sidefire mixing tube is the range of 10 to 20. This causes the resulting jet to be less collimated and less efficient in cutting.



90 Degree Sidefire Nozzle Inside a Stringer



45 Degree Sidefire Nozzle for Edge Beveling

Figure 4: Sidefire Nozzle

Figure 5 shows cutting data obtained with a sidefire nozzle for cutting carbon composites. The cutting speeds obtained with sidefire nozzles are about 50% of that obtained with a standard AWJ nozzle.

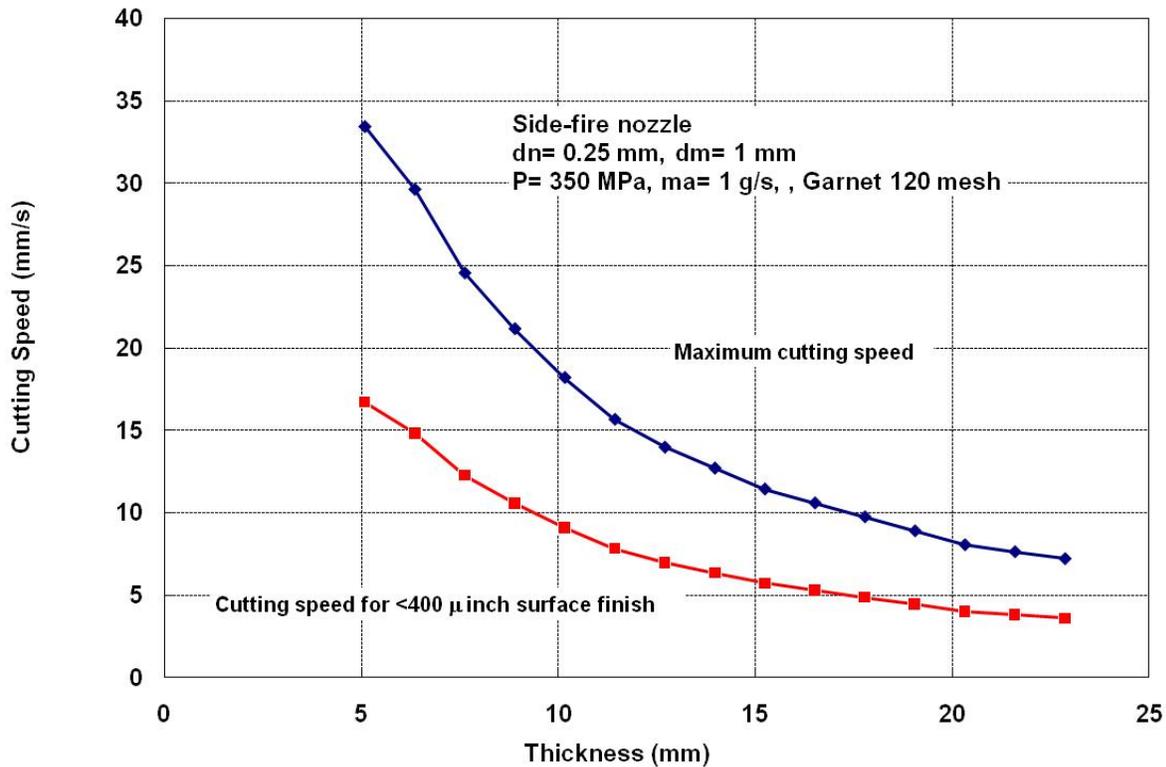


Figure 5: Results Obtained with a Sidefire Nozzle

4.3 Thin Kerf Nozzles

Thin kerf cutting is emerging for many electronic, medical, and thin sheet cutting. Miller (4, 5) investigated “micro” AWJs with promising results but no practical applications emerged yet. Hashish (6) used an AWJ with 0.38-mm mixing tube diameter for cutting and singulating micro SD cards used today in many electronic components. This represented the smallest mixing tube diameter used in a commercial application. The width of the cut was only allowed to grow from 0.04 inch to 0.5-mm as the nozzle wears out. The mixing tube diameter of 0.038-mm was the limit of what can be provided by Kennametal mixing tube material. However, with advances in mixing tube manufacturing, the use of 0.25-mm diameter mixing tubes in length reaching 50-mm is possible and is emerging.

As the mixing tube diameter is reduced, so should the corresponding orifice diameter. The orifice diameter to mixing tube ratio should not be less than 0.5 for efficient abrasive entrainment. So, for a mixing tube diameter of say 0.25-mm, an orifice diameter of about 0.125-mm should not be exceeded. This will result in lower power jets (4.4 KW at 400 MPa) with reduced cutting capability. To enhance the cutting speed, the pressure must be increased. Increasing the pressure to 600 MPa will increase the power to about 10.4 KW. Also, the jet power density will increase by a factor of 1.74. Accordingly, the strategy of reducing AWJ

diameter may be associated with increasing pressure as the only practical variable to enhance the cutting performance by both increasing the power and the power density.

The most significant problem in using relatively small diameter (less than 0.38-mm) AWJs is the abrasive feed process. First, the abrasive particle size must be reduced. Finer abrasives (finer than 180 mesh) are more problematic to feed by suction. This, however, can be enhanced by using vacuum assist, and/or feeding the abrasives in a dense wet phase as an alternative method to dry suction feed. The feeding of abrasives in a “paste” or “foam” form will allow using smaller diameter mixing tubes, but this will require development and optimization of the nozzle geometry.

Figure 6 shows an experimental nozzle (7) using a 0.025-mm orifice in a 0.18-mm diameter mixing tube at 690 MPa pressure with a vacuum assist. This proved to be capable of cutting materials such as steel and aluminum using 240 mesh dry garnet abrasive feed. Figure 7 shows example data. The 0.025-mm orifice was quickly plugged. This highlights the issue of small orifice reliability and the additional measures needed to insure that they do not get plugged or altered.

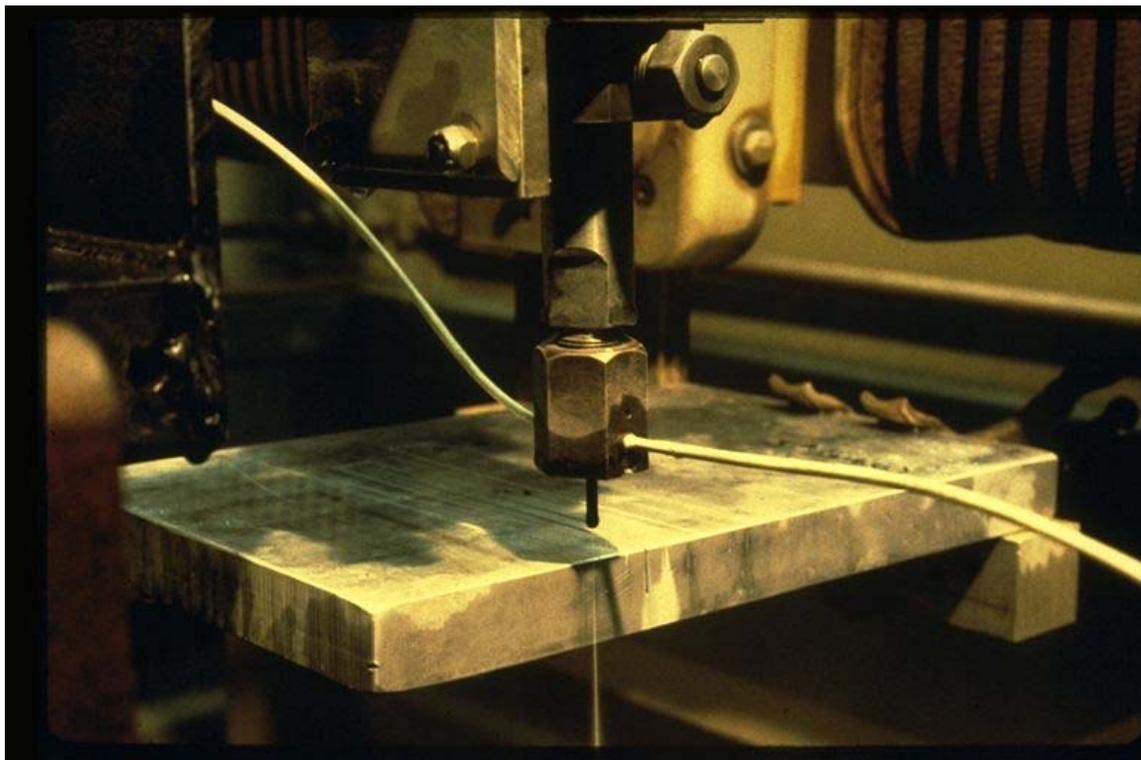


Figure 6: Thin Kerf Experimental Nozzle with 0.025-mm Orifice and 0.18-mm Mixing Tube at 690 MPa

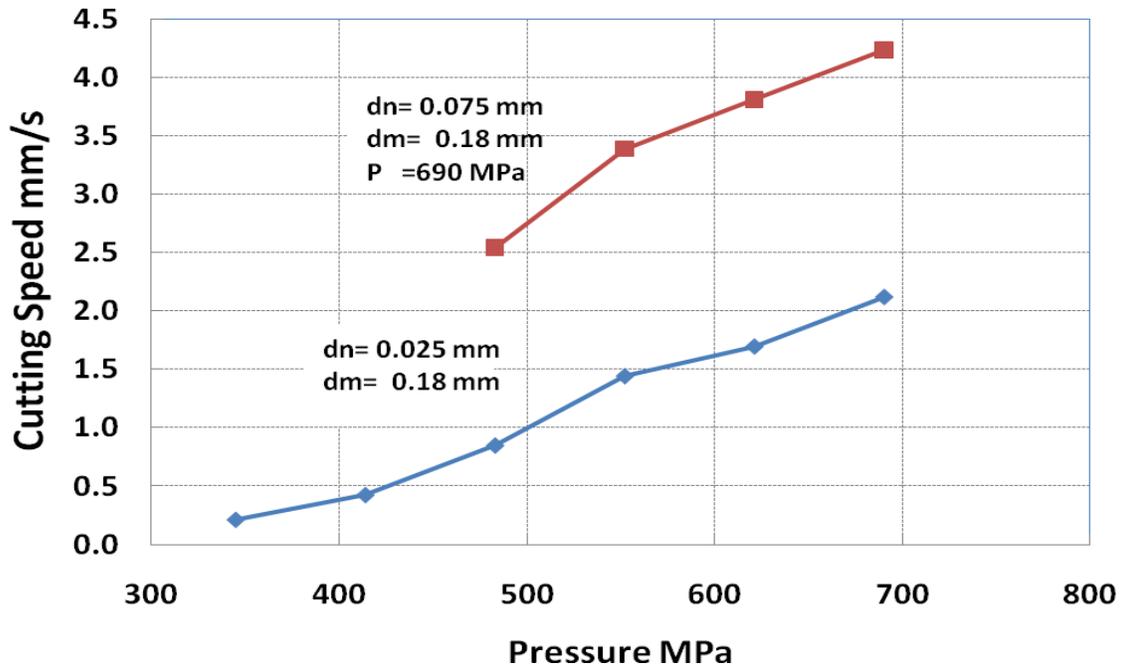


Figure 7: Cutting with 0.18-mm Diameter Mixing Tube Using 0.025 and 0.075 Orifices. Material is 1.5-mm Thick Aluminum.

4.4 Deep Kerf Nozzle

In order to cut deep into material with moderate power levels, the nozzle needs to enter the kerf (8). Accordingly, the kerf must be wide enough for the nozzle to be fed in. A deep kerf nozzle was developed using a rotating AWJ at an angle as shown in Figure 8 to widen the kerf. The diameter of the deep kerf tool must be optimized to achieve the most efficient performance. For example, the smaller the tool, the less power and abrasives it may be able to use. Larger tools will require the cutting of wider kerfs which may reduce productivity.

The deep kerf tool was used to cut large concrete sections for the decommissioning of the West Valley Nuclear Power Plant. It was found that a 25-mm diameter tool is adequate for cutting concrete sections of 5 ft thick, Figure 9. With about 100 KW tool, a 1 m²/hr kerf area can be generated. Some of the concrete deep kerfing challenges is cutting the rebars so they do not obstruct the feed-in and traverse of the deep kerf tool. A special strategy was to use a load cell on the deep kerfer to detect excess loads due to rebar obstruction. The tool will then lift slightly off the kerf and traverse over the rebar a few times until it is completely cut. The deep kerfer can then resume the kerfing cycle.

The feed of abrasives in small long passages represent another challenge to the performance of deep kerfers. It was found that a dedicated passage rather than an annular one is preferred.

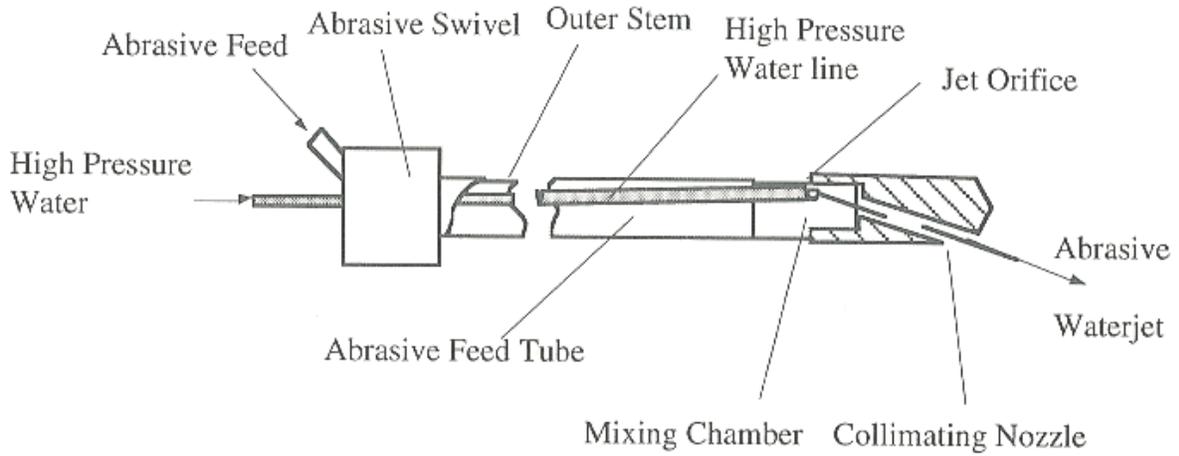


Figure 8: AWJ Deep Kerf Concept

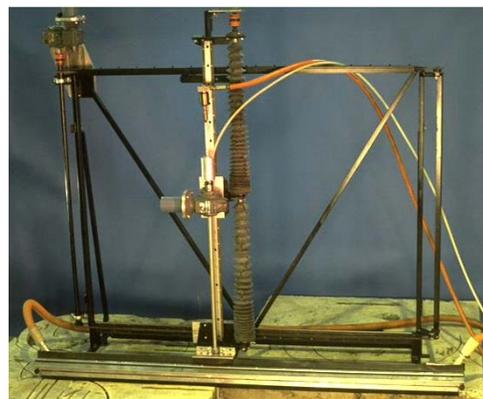


Figure 9: Cuts Made in Concrete with a 25-mm Deep Kerf Tool

5. CONCLUSIONS

A few AWJ nozzles for special applications have been discussed. This included the largest and smallest AWJs reported for use in the industry. The flexibility of the AWJ to be configured to the application is unmatched by other tools. The following are some specific conclusions:

- Deep cutting requires larger jets and higher levels of power. This requires improved jet collimation by using relatively long mixing tubes. A 900-mm long mixing tube has been built and used to cut 600-mm thick glass and metals.
- The significant problem for minimizing the size of an AWJ nozzle is abrasive feed. A different approach such as feeding the abrasives in a wet dense phase is the suggested direction.
- Sidewire nozzles are now commercially used for trimming of composite stringers for the Boeing 787 with superior performance to conventional tools.
- Deep kerfing with AWJ has been proven to cut large sections of concrete and rocks in commercial applications.

6. REFERENCES

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NOMENCLATURE

A_p	Cross-sectional area of particle	S_a	Abrasive particle specific gravity
C_d	Coefficient of discharge	U	Water velocity
C_D	Drag coefficient	V	Volume
d_m	Mixing tube diameter	V_a	Abrasive particle velocity
d_p	Particle diameter	V_j	Waterjet velocity
d_n	Nozzle diameter	V_{\max}	Maximum abrasive velocity
E	Jet hydraulic power	V_{th}	Velocity for incompressible flow
F_p	Force on abrasive particle	x	Distance along mixing tube length
l_m	Mixing tube length	λ	Particle velocity ratio
m_p	Particle mass	ρ	Water density at pressure P
\dot{m}_a	Abrasive flow rate	ρ_o	Water density at $P = 0$
\dot{m}_w	Water flow rate	ψ	Compressibility coefficient of velocity
n	Constant	ζ	Momentum transfer efficiency
P	Pressure	η	Power efficiency
r	Abrasive loading ratio		