2007 American WJTA Conference and Expo
August 19-21, 2007 • Houston, Texas

Paper

FROM A SINGLE PRODUCT (AWJ) TO A MULTI PRODUCT

ABRASIVE WATERJET INDUSTRY

D. S. Miller
Miller Innovations
Harrold, Bedford UK

ABSTRACT

Companies in the rapidly growing abrasive waterjet industry need to concentrate on securing market share for their existing AWJ products and on incrementally developing these products to meet customer needs. As the AWJ market matures and competition increases, forward planning companies will begin developing products that complement and extend abrasive waterjets to markets beyond the capabilities of AWJs. Future markets for abrasive waterjets include fine and micro machining along with dynamic machining for marking and milling.

The practical operating envelope of abrasive waterjets is described, taking account of limitations imposed by physical processes, material capabilities and engineering knowledge. Information is given on the key technologies needed to extend abrasive waterjet operations from general machining with AWJs to fine and micro machining and to dynamic machining.

Organized and sponsored by the WaterJet Technology Association

1. INTRODUCTION

1.1 Market and Research

The potential market for machining systems based on the current abrasive waterjet technology (AWJ) is over ten times the present base of about ten thousand users. In this situation manufacturers need to concentrate on selling AWJ systems and on making incremental improvements to these systems.

Many "me too" competitors have entered and continue to enter the AWJ market, competing for both abrasive waterjet equipment and complete machining systems. Leading abrasive waterjet manufacturers have a sufficiently large user base for companies specialising in spares and consumables to have entered the market and to have seriously eroded the profitable after-market of the leading AWJ manufacturers.

Major manufacturers have pushed the boundaries of engineering knowledge to produce effective and reliable AWJs. They can continue to grow through the quality of their products, their ability to meet demands for sophisticated machining systems and through their marketing and sales capabilities.

In the light of the preceding comments, it is not surprising that abrasive waterjet manufacturing companies fund little research in Universities and Research Organisations. A result is the virtual collapse of abrasive waterjet research activity in the US and Europe, particularly as government funding for research is dependent on industrial financial backing.

Currently AWJ systems from developing economies are very competitively priced but do not have the level of sophistication of systems from the US and Europe. However, this will change, particularly through the practice of integrating key components from US and other sources into machining systems predominantly manufactured in a developing country. At the same time the research base in developing countries is growing. The US and European abrasive waterjet industry needs to avoid the experience of other industries where product innovations have finished up coming mainly from developing economies.

Abrasive waterjets complement and compete with lasers. When the laser industry had reached the current stage of development of the abrasive waterjet industry innovative start-up companies were selling new types of lasers and there was a thriving laser research community. Major laser companies were able to acquire new products by buying start-up companies and/or using outputs from the laser research community for new product developments. Such a situation does not exist in relation to abrasive waterjets – there is a lack of innovative start up companies and the research base in the US and Europe is declining.

At some stage, leading abrasive waterjet manufacturers may follow the example of companies in other industries and fund directed research in centres of excellence in engineering. These centres would specialise in technologies needed for future products, rather than have a background related to research on AWJs.

As regards innovative start up companies developing new abrasive waterjet products, the best chance of this happening is for a company to support an innovative individual or team in a start-up environment. In this way a company has the possibility of having new products to exploit without being distracted from growing its AWJ business.

1.2 Incremental Improvements

An abrasive waterjet is a cutting tool that only becomes useful when integrated into a machining system. The cost of the abrasive waterjet part of a machining system may be less than 20% of the capital cost of a system but it can account for over 80% of the ongoing operating costs, excluding labour. This means a few percent points improvement in abrasive waterjet system performance can be a major selling advantage for a machining system manufacturer. In this situation, incremental improvements in AWJ cutting performance, reliability and usability become extremely important.

The scope for patent protection on incremental improvements is limited so other companies can soon replicate improvements. AWJs are reaching the stage of development where incremental improvements are becoming harder to achieve and there is already evidence of an industry-wide convergence towards AWJ systems of similar performance, reliability and usability. This situation is good news for the end-user but will increase the pressure on manufacturers to develop new abrasive waterjet technologies.

A question is, when will it become more attractive to develop complementary products compared to achieving incremental advances? To aid in answering this question, better insights are required into the physical phenomena involved in abrasive waterjet generation and cutting.

1.3 Understanding of Abrasive Waterjet Technology

AWJs have evolved through a pragmatic engineering approach that has pushed mechanical, material and manufacturing technologies to their limits. What the evolutionary process has not done is to advance the understanding of the physical processes involved in abrasive waterjet generation and how abrasive waterjets cut. Thoughts held early on about how abrasive waterjets are generated and how they cut have become accepted even though they assume processes that are physically impossible. In other words, accepted beliefs about how abrasive waterjets work are myths (www.abrjet.com). Section 2 looks at two of the most important myths to provide the base for the remainder of this paper.

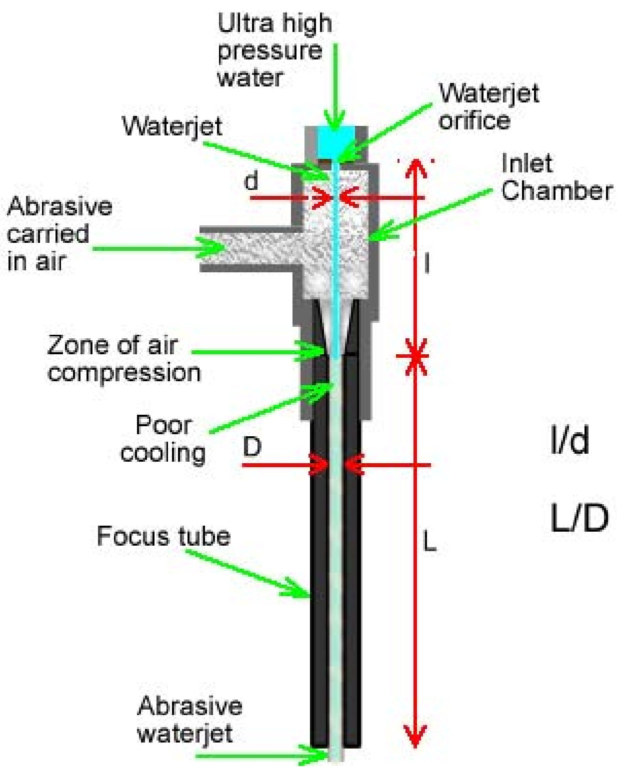
2. MYTHS ABOUT ABRASIVE WATERJETS

Aspects of abrasive waterjets that are taken for granted need to be reinterpreted to:

- Gain a better understanding of the operating envelope for abrasive waterjets
- Make better judgements on how to improve the performance of AWJs
- Aid in the development of new types of abrasive waterjets
- Provide insights on which to base research studies.

2.1 AWJs do not operate like jet pumps

Explicitly or implicitly, published models of AWJ cutting head flows assume that flow phenomena in cutting heads are similar to those in jet pumps. Two important non-dimensional geometric parameters for the two devices are shown in Figure 1. In terms of non-dimensional geometric parameters, jet pumps are compact devices compared to AWJ cutting heads. The large differences in non-dimensional geometric parameters between the devices arise from their operating modes.



	Jet pump	AWJ
l/d	< 4	40 to 60
L/D	< 8	> 60

Figure 1. Non-dimensional length parameters for jet pumps and AWJ cutting heads

A jet pump has a concentrated momentum exchange zone where the driving fluid and the entrained fluid are turbulently mixed to transfer momentum from the driving fluid to the entrained fluid. There is an increase in static pressure of the entrained fluid but the energy efficiency of a jet pump is usually below 30%. Clearly a jet pump is first and foremost an energy dissipater so it is important that flow phenomena in AWJ cutting heads do not mimic those of jet pumps. Air occupies over 90% of a focus tube bore and its low density, relative to water, prevents turbulent mixing of the form that occurs in jet pumps.

Momentum exchange in an AWJ cutting head occurs over two extended regions. The first region is the inlet chamber where momentum is predominately transferred from a waterjet to air. The second region is in a focus tube bore, where momentum is transferred from water to abrasive particles in interactions between abrasive and water in jet, slug and droplet form.

As it traverses an inlet chamber, drag from a waterjet and droplets ejected from a waterjet move air and abrasive towards a focus tube inlet and provides a mechanism to compresses air just prior to its entry into a focus tube bore (www.abrjet.com). Air compression provides the means to entrain sufficient air to carry abrasive to a cutting head.

An AWJ cutting head is a unique two stage fluid dynamic device that involves an air compression stage followed by a momentum exchange stage between water and abrasive.

Illustrations in the literature of flows within cutting heads consistently foreshorten the distance over which abrasive waterjets break up. The assumption is made that abrasive, water and air mix in a cutting head inlet chamber and focus tube inlet. There is no known flow process that could cause such mixing, as it requires the disintegration of a high velocity waterjet without the forces to cause such disintegration. In reality, a waterjet is essentially intact as it enters a focus tube bore. The distance before a waterjet is effectively broken up affects how focus tubes wear, as described in the next sub Section.

2.2 Abrasive waterjets are not cold cutting tools

Abrasive waterjets are marketed as cold cutting tools and nearly all research studies assume a cold cutting process. It is impossible to machine metals and other materials rapidly without reaching temperatures that cause a major change in a material's state (Ojmertz 1997, Hoogstrate 2002).

Abrasive waterjet cutting is a thermal cutting process involving temperatures that are sufficiently high to melt a material. Uniquely, the cutting process is accompanied by extreme cooling that virtually eliminates heat effects on cut surfaces.

Figure 2. Cutting Translucent Aluminum Oxide (© Christian Ojmertz)

High speed abrasive particles impacting on a material create temperatures related to the melting temperature of the material, unless the material has a higher melting temperature than the abrasive, when temperatures are related to the abrasive melting temperature. Figure 2 is a photograph (Ojmertz 1997) of an abrasive waterjet cutting translucent aluminium oxide with garnet abrasive. The melting temperature of garnet is 1280° C whilst the melting temperature of aluminium oxide is 2030° C. The light emitted from the cutting face is associated with garnet melting.

Understanding the thermal nature of abrasive waterjets is particularly important as regards focus tube materials. Referring to Figure 1, at entry to a focus tube a waterjet occupies the centre 10% of a focus tube bore with a small percentage of water flow in the form of droplets surrounding a waterjet. The most extreme erosive conditions occur in the first part of a focus tube bore and this is where there is little cooling of a bore wall. This means a material used for a focus tube must have extremely good wear properties that do not deteriorate significantly at temperatures above the melting temperature of the abrasive. This is considered further in Section 4.3.

3. OPERATING ENVELOPE FOR ABRASIVE WATERJETS

Power input considerations limit maximum cutting jet diameters to about 1.5 mm, whilst difficulties in control over abrasive particle sizing will probably place a lower limit of 10 microns or so on the minimum cutting jet diameter. Abrasive waterjet cutting performance and capabilities depend on many factors that include power input, water pressure, abrasive waterjet generation method and cutting jet on/off cycle times.

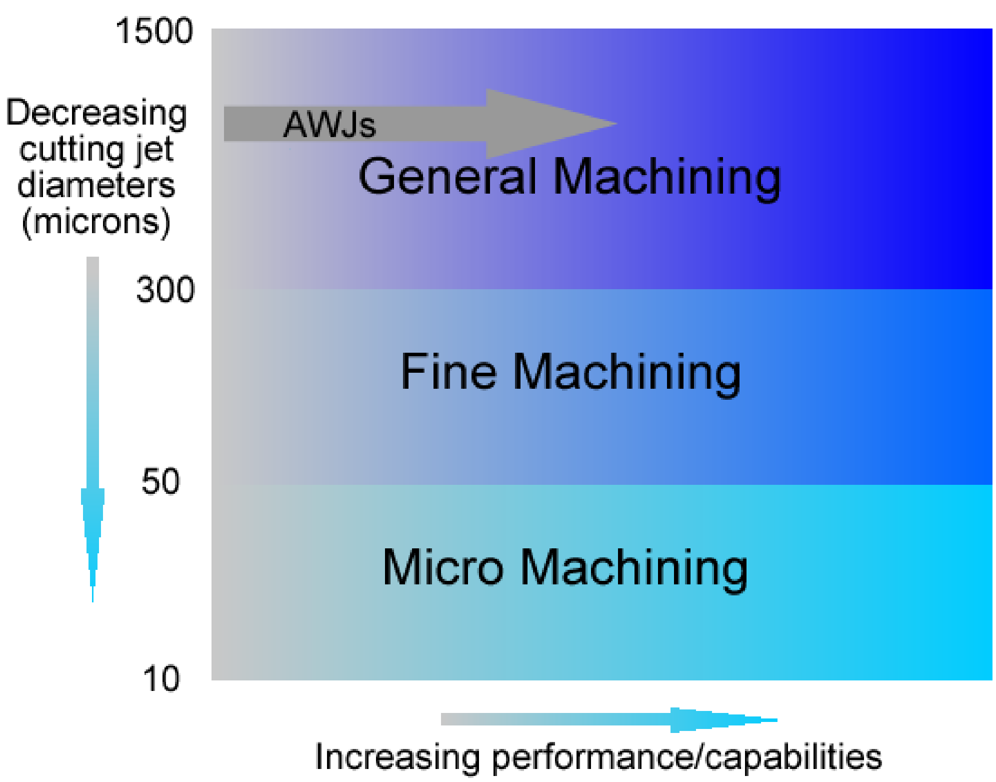


Figure 3. Practical Operating Envelope for Abrasive Waterjets

Figure 3 shows schematically the operating envelope for abrasive waterjets. Currently only AWJs are exploited commercially. Performance of AWJs is rising mainly through increased water pressures and power inputs.

Abrasive waterjets are shown on Figure 3 as falling into three machining areas – general, fine and micro. This classification is convenient as each area involves a different method of generating an abrasive waterjet:

- General machining (AWJs) - generated by entraining abrasive carried in air (potentially also steam) into a high velocity waterjet to form a cutting jet with a diameter between 300 microns and 1.5 mm
- Fine machining (FAWs) - generated by entraining abrasive carried in water into a high velocity waterjet to form a cutting jet with a diameter between 50 microns and 300 microns
- Micro machining (MAWs) - generated by passing a pressurised suspension of abrasive in water through a cutting nozzle to form an abrasive cutting jet with a diameter less than 50 microns.

Flow circuits for entrainment and suspension systems are shown schematically in Figure 4.

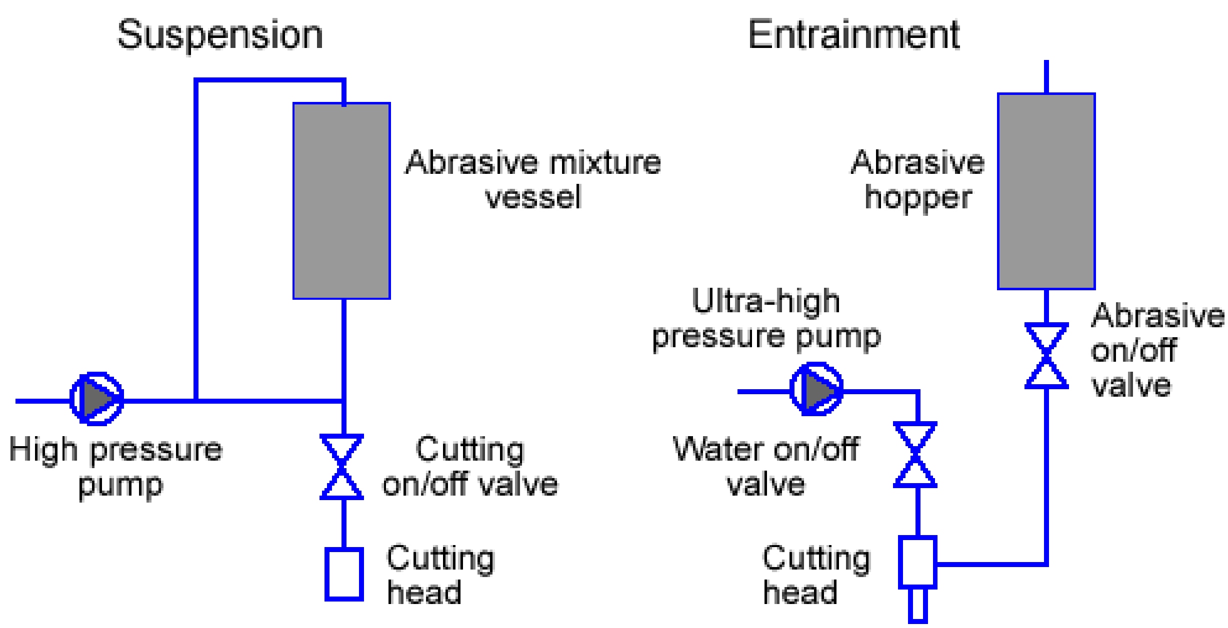


Figure 4. Schematic flow circuits for suspension and entrainment abrasive waterjets

The advantage AWJs have over other methods of abrasive waterjet generation are that they use abrasive that is free flowing in air, the abrasive is easy to meter and is handled at near atmospheric pressure. Abrasive for cutting jets less than 300 microns is not free flowing in air because of electrostatic forces and problems with moisture absorption onto particles. This means abrasive has to be suspended in water in order that it can be induced to flow to a cutting head to be entrained into a high velocity waterjet.

MAWs are generated by the highly efficient method of passing abrasive suspended in pressurised water through a cutting nozzle. Reliability and other issues limit the use of suspension systems to micro abrasive waterjets (www.abrjet.com). MAWs use less than a kilogram of abrasive per hour and the efficiency of abrasive jet generation provides good cutting capabilities at water pressures below 1000 bar, compared to over 3000 bar needed by AWJs. Operating with low abrasive flow rates and high, rather than ultra high, pressures allows simple flow circuits and robust system construction.

AWJs are not dynamic cutting tools because of the need to dynamically suspend and carry abrasive to a cutting head and clear abrasive before a waterjet is stopped - a laser can go through a thousand or so cutting cycles in the time that an AWJ goes through one cycle. FAWs and MAWs use abrasive suspensions so the abrasive is statically suspended and remains in a cutting head when water flow is stopped. With abrasive remaining in a cutting head, FAWs and MAWs can start and stop machining 10 to a 100 times faster than AWJs.

4. KEY TECHNOLOGIES FOR NEW ABRASIVE WATERJET SYSTEMS

4.1 Abrasive

The rapid exploitation of AWJs owes much to the availability of garnet abrasive in appropriate grain sizes and to the ease with which the abrasive can be metered and carried by airflow in tubing. Abrasive handling deteriorates for particle sizes needed for FAWs. If abrasive is dry electrostatic forces cause particles to attach to tube walls and to one another, and if abrasive is left in contact with atmospheric air it readily absorbs moisture and particles clump together.

Suspending fine abrasive in water so that it can flow and be metered introduces many more variables than are involved when abrasive can be carried in air. Also the classification of abrasive becomes much more difficult as particle diameters decrease. The success of FAWs and MAWs will dependent on quality control over abrasive and how it is packaged so that prepared abrasive mixtures remain free flowing and uncontaminated. It is, therefore, likely that FAW and MAW system manufacturers will need to control the classification and packaging of abrasive, probably as a suspension with additives, and that the abrasive will be provided in proprietary cartridges.

4.2 Waterjet nozzles

Reduced focus tube wear and higher cutting performance require changes in AWJ cutting heads that need waterjet orifices to be replaced by waterjet nozzles (www.abrjet.com). Using a waterjet nozzle the fluid dynamics of cutting heads can be improved, with greater control over airflow and the acceleration of abrasive particles into a focus tube. Improvements in manufacturing methods will make waterjet nozzles competitive in price with diamond orifices.

4.3 Focus tubes and cutting nozzles

As discussed in Section 2.2, temperatures in AWJ focus tubes reach the melting temperature of garnet or other abrasive. Originally focus tubes were made of cemented tungsten carbide that had a cobalt binder. The melting temperature of cobalt is 1495° C but its physical properties deteriorate below this temperature. The melting temperature of garnet at 1280° C is too close to the melting temperature of cobalt for cemented tungsten carbide to be a satisfactory material for focus tubes. It was the only material with a useful life in the formative years of AWJ development.

In the early 1990s, sub-micron grain composite tungsten carbide materials were introduced that contain vanadium carbide or molybdenum carbide with little or no soft binder - known as ROCTEC ® and now produced by the sole licencee Kennametal. Focus tube lives increased from under ten hours or so for cemented tungsten carbide to eighty hours or so for composite tungsten carbide. Composite tungsten carbide focus tubes are credited with making the widespread exploitation of abrasive waterjets possible.

Trials on alternative ultra hard materials for focus tubes have not identified materials that match the performance of composite tungsten carbides. This may be due to trials on alternative materials not being planned to discover materials capable of good wear performance at high temperatures. Before materials are selected for trials, informed assessments need to be made by material specialists on factors such as high temperature properties, catalytic reactions, rapid corrosion, oxidisation and likely micro-cracking characteristics.

Materials such as polycrystalline diamond may have good wear characteristics when used with garnet abrasive sized for MAWs but poor wear characteristics when garnet abrasive appropriate to AWJs is used. It is, therefore, desirable to test candidate materials over a range of abrasive sizes.

The dimensions of focus tubes for FAWs and cutting nozzles for MAWs are sufficiently small that polycrystalline and chemical vapour deposition diamond are candidate materials. It has been found (www.abrjet.com) that abrasive particles used by FAWs and MAWs are sufficiently small that particle impact damage on polycrystalline diamond is acceptable.

It should be noted that although FAWs entrain abrasive suspended in water this does not eliminate the zone of poor cooling in the first part of focus tube bores. Super cavitation occurs in FAW cutting heads that creates large vapour cavities that can be expected to prevent intense cooling in the first part of a focus tube bore.

Anecdotal evidence points to composite tungsten carbide having similar wear performance to composite tungsten when used for suspension abrasive waterjet cutting nozzles. The bores of cutting nozzles have good wall cooling conditions near their inlets. However, towards focus tube outlets a bore wall is subjected to extreme temperatures and pressure loads due to the collapse of cavitation bubbles. It may be found that a super hard material that performs poorly when used for focus tubes perform well when used for cutting nozzles because they resist cavitation damage.

4.4 Valve seats

Shut off valves on AWJ cutting heads operate for 100,000 or so opening and closing cycles before seat failures occur as a result of:

- An axially moving plug, that forms a seat, impacting on a second fixed seat during valve closure. Seat-to-seat impacts cause microscopic damage that grows with the number of closing actions.
- Erosion by water travelling at 800 m/s or so on initial valve opening and just prior to valve closure
- Cavitation damage during initial opening and final closure valve of seats.

Because AWJs are used for machining tasks that do not require short cutting cycles, a valve seat life of 100,000 opening and closing cycles can represent thousands of hours of machining time, which is an acceptable life.

A shut off valve on a FAW or a MAW could accumulate 100,000 opening and closing cycles in a few hours, so valves similar to those used on AWJs are not suitable for FAWs and MAWs. Also MAW valves pass a suspension of abrasive particles and need seats made of a super hard material. Super hard materials are brittle requiring a change in valve action from axial seat motion as used for AWJ valves to seats sliding relative to one another. Sliding seat valves have been developed for FAWs and MAWs (www.abrjet.com).

4.5 Ultra high pressure pumps

FAWs operate with similar water pressures to AWJs. Since AWJ intensifier pumps can operate down to zero flow, a FAW cutting head can be powered by an AWJ pump. This may be a satisfactory solution when a FAW is integrated into an existing AWJ installation. However, a new generation of ultra high pressure pumps is required for stand alone FAWs since there are no suitable ultra high pressure pumps designed to supply a few litres of water per hour.

A low flow, ultra high pressure, direct driven plunger pump has been developed for FAWs (www.abrjet.com).

4.6 High pressure pumps

MAWs operate at pressure below 1000 bar and with flows less than 3 litres per hour. Pumping duty for MAWs can be met by:

- Two pneumatic driven, intensifier plunger pumps with a programmable logic controller to synchronise plunger movements to minimise pressure fluctuations.
- A pair of roller or ball screw actuated plunger pumps operating in synchronous mode
- A rotary multi plunger pump with an electric drive.

Power input to a MAW pump is below a kilowatt, allowing the use of single-phase electrical supplies.

5. DISCUSSION

The abrasive waterjet industry is currently a single product industry in terms of abrasive waterjet generation (AWJ). With a rapidly growing market for AWJ systems, being a single product industry is not a problem. However, the cyclic nature of the machine tool market means that at some stage the abrasive waterjet industry will find it has over capacity, with all the attendant financial problems for companies.

Market downturns are often out of phase across different market sectors so to mitigate the effects of market downturns companies seek to diversify their product portfolio. An example of this is the laser machine tool industry where companies evolved from a single product – one cutting beam generation method – to companies providing a range of products – several cutting beam generation methods.

The market for micro machining laser systems developed ten years behind that for general machining lasers but within the next five years the value of micro machining laser sales are predicted to match those of general machining lasers. Applications where AWJs have advantages over general machining lasers carry through to micro machining. It can, therefore, be expected that, in the long term, revenues from MAW based machining systems will be similar to those from AWJ based machining systems

To show that abrasive waterjets can contribute to product and process miniaturisation, the author has cut stainless steel with 50 nanometer diameter abrasive particles in a waterjet. Practicalities associated with abrasive sizing and contamination limit cutting jet diameters to the micron diameter range but at least it is known that cutting does not stop because particles are too small.

The dynamic machining capabilities of FAWs and MAWs enable multiple features to be machined per second, such as drilling holes in foil materials and in marking of parts. FAW and MAW jets start cutting as water flow is established, allowing machining of fragile materials that crack and spoil on commencement of cutting with an AWJ.

Examples of applications for micro abrasive waterjets are given in (www.abrjet.com), where it is stressed that FAWs and MAWs are ideal for small job shops who need the ability to process a wide range of materials. A feature of the micro machining laser industry is the number of manufacturers who carry out jobbing activities to support product development and to machine parts for customers before selling them a machining system. Jobbing work is likely to be important to the development of MAW machining systems.

Whilst designing and building demonstration FAW and MAW systems, the author has not come across any barriers that would prevent industry-worthy systems being developed. That is to say, manufacturing technologies are available to produce FAWs and MAWs, commercially viable cutting rates are achievable, cutting systems should be easy to use and can be engineered to be reliable.

6. CONCLUSIONS

1. The abrasive waterjet industry is on a steep growth curve, with many "me too" manufacturers building on the pioneering work of the leading AWJ manufacturers.
2. Manufacturers will begin looking for new products that complement AWJs when there are sufficient business pressures to do so. These pressures are likely to come from; a recession in the general machining market, increasing competition, the onset of market saturation, customer needs for new capabilities, or a combination of these factors.
3. Only part of the practical operating envelope of abrasive waterjets is currently being exploited so there is the opportunity for new products.
4. Technologies and manufacturing methods are available to build machining systems based on fine and micro abrasive waterjets.

7. REFERENCES

Hoogstrate, A.M., Karpuschewski, H.B. "Modelling of the Abrasive Waterjet Cutting Process in a Modular Way" Proceedings of the 16th International Conference on Water Jetting, 2002, BHR Group, Cranfield, UK.

Ojmertz, C., (1997) "A Study of Abrasive Waterjet Milling" Dept of Production Engineering, Chalmers University of Technology, Goteborg, Sweden.

www.abrjet.com - The author's web site contains extensive information on the fluid dynamics of abrasive waterjets and on their capabilities.

8. NOMENCLATURE

AWJ — Abrasive waterjet generated by entraining abrasive carried in air into a high velocity waterjet; also the equipment used to generate an AWJ. AWJs have cutting jet diameters over 300 microns in diameter.

FAW — Abrasive waterjet generated by entraining abrasive suspended in water into a high velocity waterjet; also the equipment used to generate a FAW. FAWs have cutting jet diameters that can range from 50 to 300 microns.

MAW — Abrasive waterjet generated by passing abrasive suspended in water through a cutting nozzle; also the equipment used to generate a MAW. MAWs typically have cutting jet diameters under 50 microns.

Focus tube (also called mixing tube or cutting nozzle) - located after a waterjet orifice or waterjet nozzle and into which a waterjet entrains abrasive in a carrier fluid. Momentum is exchanged between water and abrasive in the bore of a focus tube to produce a cutting jet at a focus tube outlet.

Cutting Nozzle – passes a suspension of abrasive in pressurised water to produce a cutting jet.