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Paper

NEW ABRASIVE WATERJET SYSTEMS TO COMPETE WITH LASERS

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ABSTRACT

Four abrasive waterjet generating modes are known but only one mode has been commercially exploited. Using all four modes extends the operating envelope of abrasive waterjets to cover a similar range of cutting beam diameters as lasers. The paper describes how an understanding of cutting head fluid dynamics allows abrasive waterjets to enter the fine and micromachining markets that are currently the exclusive domain of lasers. It also describes how the cutting performance of general machining abrasive waterjets can be improved to better compete with lasers.

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1. INTRODUCTION

Abrasive waterjets are classified as power beams along with lasers, with which they share similar requirements from motion, control and software systems. Abrasive waterjets both complement and compete with lasers, with laser job shops being a major purchaser of abrasive waterjets.

Only one mode of generating abrasive waterjets has been effectively exploited for precision machining and this mode cannot be used for fine and micro machining. A similar situation existed with lasers up until the early 1990s when lasers for fine and micro machining began to be exploited. Numerous applications exist for fine and micro abrasive waterjet systems and the technologies now exist to profitably manufacture and use fine and micro abrasive waterjets.

Over the past twenty years the cutting performance of abrasive waterjets has doubled as water pressures have increased to 4000bar or so. However, ultra high-pressure pumps for general machine shop use have more or less reached a pressure plateau, so it is necessary to look elsewhere for further improvements in cutting performance.

The component unique to abrasive waterjets is the cutting head and it is the fluid dynamics of a cutting head that determines cutting performance. This paper describes how a better understanding of the fluid dynamics of abrasive waterjet cutting heads and their feed systems has resulted in:

- Systems to generate micromachining abrasive waterjets (MAWs) by passing a suspension of abrasive particles in pressurised water through a nozzle. This mode of abrasive waterjet generation is particularly effective for generating jets with diameters less than 50microns
- Entrainment cutting heads that entrain a high concentration abrasives/water mixture into a high velocity waterjet to generate a cutting jet (FAWs). This mode of abrasive waterjet generation is particularly effective for generating jets with diameters in the range 50 to 300 microns
- Radical design changes to conventional abrasive waterjet (AWJ) cutting heads to improve cutting performance and to replace their relatively short life waterjet generating orifice with a waterjet generating means that has a virtually infinite life
- Development work on cutting heads that use a condensable vapour (steam) as the abrasive carrier fluid (SAWs). Condensing a carrier fluid in a focus tube allows cutting jet diameters to be reduced relative to AWJs, thereby raising cutting speeds as less material is removed to make a cut
- Abrasive waterjets becoming dynamic machining tools in comparison to AWJs that have static machining characteristics. Dynamic capabilities are achieved by suspending statically abrasive in a carrier fluid so that virtually instantaneous starting and stopping of cutting is possible, whereas AWJs have to suspend abrasive dynamically before cutting can commence. AWJs need to consume all suspended abrasive before cutting is stopped. Dynamic capabilities open up many new applications for abrasive waterjets.

The factors that control the cutting performance and operating range of abrasive waterjets are outlined in Section 2, followed by a discussion on the fluid mechanics of cutting heads in Section 3.

Intensifier and crank pumps that power AWJs are too powerful for FAWs and MAWs, although FAW machining capabilities can be readily added to an AWJ cutting system that is powered by an intensifier pump since these pumps can run at low flows. Low flow pump options are discussed in Section 4 with comments on pumps used for the development of FAWs and MAWs.

Experiences and lessons learned from operating FAWs and MAWs are contained in Section 5. Comments on a licensing strategy are included in Section 6, with conclusions in Section 7.

2. CUTTING PERFORMANCE AND OPERATING ENVELOPES

2.1 Ideal Operating Mode

It is useful to compare the cutting performance of abrasive waterjet generation modes against an ideal generation mode. The ideal mode involves passing a suspension of abrasive particles in pressurised water through a nozzle. Energy losses in a nozzle are 10% or so of the incoming water energy. Abrasive particles reach a workpiece travelling at virtually the same velocity as water and produce a cut with a width marginally larger than the nozzle diameter. The ideal mode of abrasive waterjet generation is only practical for MAWs and then at lower water pressures than used for AWJs and FAWs.

2.2 Cut Width

The amount of workpiece material removed to make a cut has a major impact on cutting performance. Cutting jet diameters of AWJs are 3 to 4 times their waterjet vena contracta diameters. As a result AWJs remove 3 or so times as much material to make a cut as ideal cutting jets. Theoretically the performance of an AWJ could be 300% higher if the cutting jet diameter was a minimum for a given water and abrasive flow. Clearly developments are needed that reduce cutting jet diameters relative to AWJs.

2.3   Kinetic Energy Transfer

Abrasive particles leaving an AWJ focus tube have a wide range of velocities. The mean kinetic energy of the particles is probably less than 70% of that of an ideal cutting jet. There is scope for improving energy transfer to abrasive particles and increasing cutting performance by 10 to 20% but this is small compared to the potential improvement from reducing cutting jet diameter.

2.4   Water Pressure

At a constant water flow, cutting speed varies more or less linearly with water pressure. Increasing water pressure from 4000 to 4400bar gives a 10% increase in cutting speed of an AWJ but at a high price in terms of pump reliability. For the foreseeable future significant increases in pump pressures for general AWJ machining applications are unlikely but improvements in pump reliability and serviceability will continue to provide commercial advantage.

MAW water pressures are limited to 700bar or so by abrasive metering and feed system operability and reliability considerations. As MAW jets have four to five times the cutting energy density of an entrainment jet, for the same water pressure, the performance of a MAW at 700bar is impressive. For the present the objective is to exploit MAWs commercially before trying to operate at higher water pressures.

2.5 Operating Envelopes

Trials with 300 and 50nanometer diameter particles in 40micron diameter waterjets (Miller 2003) have shown that these particles cut the same materials as conventional abrasive waterjets. It should, therefore, be possible to operate abrasive waterjets with micron and sub-micron diameters. However, current abrasive quality assurance and system cleanliness procedures are only adequate for minimum cutting jet diameters of 50microns or so (Miller 2005).

Cutting jet diameter envelopes for the four abrasive waterjet generation modes are shown on Figure1 along with the cutting beam diameter envelope for lasers.

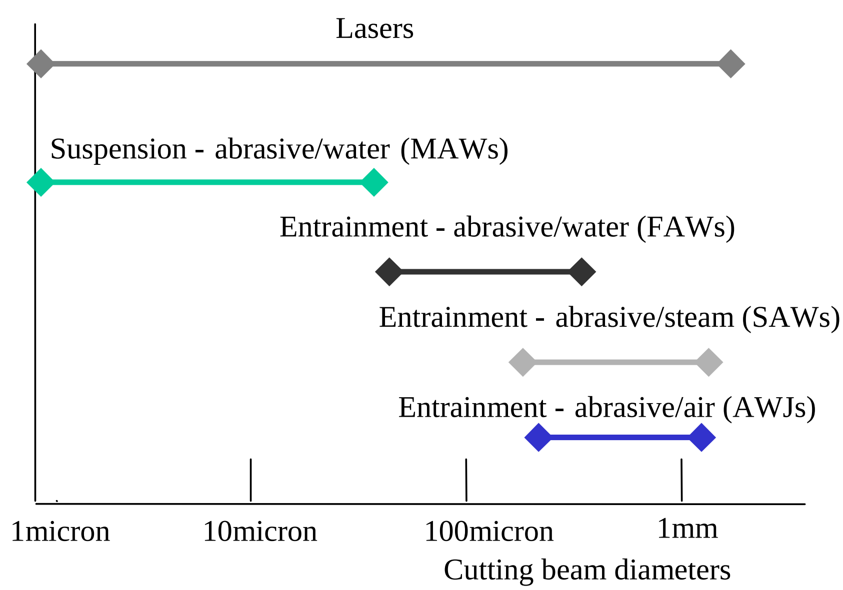

Figure 1. Cutting beam diameters for abrasive waterjets and lasers

AWJs rely on the free flowing properties of dry abrasive and a sufficiently high airflow to suspend and transport abrasive particles. Below cutting jet diameters of 500microns airflows drop below those required to reliably suspend and deliver abrasive to cutting heads. Auxiliary means can be used to maintain abrasive flow down to cutting jet diameters of 300microns or so. Below 300microns, abrasive has to be suspended in water because electrostatic and inter-particle forces and absorption of moisture by abrasive make it impractical to use air as a carrier fluid.

Entraining abrasive/water mixtures extends the operating envelope of entrainment cutting heads down to 50microns or so. The minimum jet diameter being limited by problems of physically providing abrasive mixture flow passages within a cutting head.

By replacing air with steam that can be condensed in a focus tube/nozzle (SAW) it is expected that a smaller cutting jet can be produced relative to an AWJ operating with the same water and abrasive flow rates. The operating envelope of SAWs is expected to be similar to AWJs that have vacuum assist to allow operation down to jet diameters of 300microns or so.

MAWs operate with pressurised abrasive/water mixtures. The equipment for MAWs needs to be simple with pressurised abrasive confined to a storage vessel just upstream of a nozzle. System simplicity is achieved by operating in batch mode so that abrasive is only transferred to a MAW when it is unpressurised. By limiting MAW cutting jet diameters to 50microns or so the fraction of a kilogram of abrasive per hour needed by a MAW can be loaded into an abrasive storage vessel contained within in a cartridge (Miller 2004).

Figure 2 illustrates the relative size of cutting heads for SAWs, FAWs, and MAWs.

Figure 2. SAW, FAW and MAW cutting heads

3. FLUID DYNAMICS OF CUTTING HEADS

3.1. AWJs

The AWJ mode of operation is elegantly simple, but important fluid dynamic processes within AWJ cutting heads are not understood. Numerous complex physical phenomena occur simultaneously, with kinetic energy densities orders of magnitude higher than in other industrial flow processes.

Forty or so companies manufacture AWJ cutting heads so one might expect that cutting head geometries that provide optimum cutting performance have been found. In reality manufacturers have all been optimising one of a number of fundamentally different combinations of fluid flow processes that can be induced to occur in AWJ cutting heads. The combination of flow processes in current AWJ cutting heads was appropriate for the technologies available when cutting heads were developed over 20 years ago. However, developments in materials and machining technologies now allow a more effective combination of flow processes to be used.

In redesigning AWJ cutting heads the author has followed design guidance on internal flows (Miller 1990) related to minimising flow separation in high-energy flows, particular when compressible flows are involved. AWJ cutting heads are unique in that separated, multi-phase, compressible flows exist in all flow passages. Air velocities exceeding twice the speed of sound in air and water velocities exceeding half the speed of sound in water. Separated flows induce high levels of turbulent mixing, resulting in high-energy losses. By reducing the extent of flow separation, and relying on pressure driven entrainment, rather than turbulent mixing entrainment, the combination of flow processes in a cutting head can be altered towards lower energy dissipation, more efficient processes.

The author believes that one cutting head design, for which patent protection is being sought, has a combination of flow processes that will provide better cutting performance than current AWJ cutting heads. The design aims to control the static pressure distribution through a cutting head so as to maintain supersonic airflow along the full length of a focus tube bore with minimal losses due to shock waves. To achieve this changes are required in the waterjet generating means, in the design of the flow passages before abrasive enters a focus tube and in abrasive/air feed conditions. Changes to the waterjet generating means eliminates problems of damage to sharp-edged orifices that are currently used to generated waterjets.

3.2. SAWs

As discussed in Section 2.2 the best chance for substantially increasing cutting performance is to reduce cutting jet diameters for a given water flow and pressure. Ideally, once air has carried abrasive into an AWJ focus tube, the air should be bled off to just leave abrasive and water. Without the air the diameter of the focus tube could then be reduced. In reality, is it is not practical to get rid of the air from a focus tube, but if air is replaced by steam the steam can be condensed to leave abrasive and water. The quantity of steam needed is only about 1%wt flow of water so steam generation can be engineered into an abrasive feed system without too many difficulties. The main problems to be overcome in developing SAWs are not wetting abrasive before it enters a focus tube and designing an effective cutting head. An abrasive hopper with a heated outlet section is being manufactured for trials with the cutting head shown in Figure 1. Using steam as the carrier fluid and condensing it in a focus tube is the subject of a patent application. A patent has also been filed for an abrasive feed hopper for SAWs.

3.3. FAWs

FAWs have jet diameters that range from 50 to 300microns or so and are generated by entraining a high concentration suspension of abrasive particles in water into a high velocity waterjet. Suspending abrasive in water to be entrained into a high velocity waterjet means that a waterjet has to accelerate a mass of water as well as abrasive. By using abrasive/water mixtures with over 60%wt abrasive the mass of the carrier water to be accelerated in focus tubes can be minimised. Currently the author is trying to establish whether operating entrainment heads with abrasive/water mixtures allows the ratio of focus tube bore diameter to waterjet diameter to be reduced relative to AWJs. As regards cutting performance, if the ratio of focus tube bore diameter to waterjet diameter can be reduced this would more than compensate for the loss in performance from accelerating the water component of abrasive mixtures.

An uncertainty in the fluid mechanics of FAWs is the effect of cavitation. The cavitation number, which is the ratio of water vapour pressure to the waterjet dynamic pressure, is virtually zero so a state of super cavitation exists where the waterjet and abrasive mixture meet. However, the super cavitation region is modified by the presence of abrasive in unknown ways. So far the author has investigated too few geometric arrangements to begin to draw any conclusions about cavitation effects.

3.4 MAWs

MAWs have jet diameters less than 100microns and are generated by passing a pressurised suspension of abrasive in water through a diamond nozzle. The fluid dynamics of MAW cutting heads are simple in comparison to entrainment cutting heads. Pressurised water carrying abrasive accelerates in the inlet to a nozzle dragging particles into the nozzle bore, where particles are accelerated to close to water velocity. Typically 10 bore diameters is sufficient length to accelerate particles but 20 or so diameters may be used to provide longer nozzle life.

The simplicity and effectiveness of suspension jet cutting heads comes at a high price in terms of the abrasive feed system. Only at cutting jet diameters sufficiently small that abrasive consumption falls below a kilogram or so per hour can reliable abrasive feed systems be engineered (Miller 2003). For higher abrasive flow rates two abrasive storage vessels are necessary to provide a continuous abrasive supply and this requires eight or more valves that cannot be engineered to be reliable when passing abrasive.

4. PUMPS FOR FAWs AND MAWs

4.1 Pumps for FAWs

FAWs require similar water pressures to AWJs of 2500 to 4000bar. The flow rates from existing ultra high-pressure (UHP) pumps are higher than those required for a single FAW cutting head. UHP intensifier pumps have the capability to operate down to zero flow so they can feed a single FAW cutting head. This means that fine abrasive cutting capabilities could be provided as an add on to AWJ machining systems, particularly for cutting tables designed for multiple cutting heads.

Pump options specifically for FAWs include:

- Hydraulically driven lower flow UHP intensifier pumps that are smaller versions of existing pumps
- An experimental roller cam (RC) pump operating at 2000 to 3000bar is being used for development work on 90micron diameter FAWs. The RC pump is a cross between a rotary and an intensifier pump and could form the basis for a family of low flow UHP pumps for FAWs. The pump has the capability to be used in start/stop mode to machine multiple features per second. A patent application has been filed for the pump
- Linear electrical drives are available that have the thrust and life cycle capabilities to power pumps for FAW cutting jets under 100microns diameter. Pumps driven by linear actuators would be particularly suited to machining systems designed for generating multiple features per second, such as holes in foil materials or blind holes in substrates.

4.2 Pumps for MAWs

For a number of technical reasons it is desirable to limit the operating pressure of MAWs to under a 1000bar. Fittings and other components are widely available for 700bar (10,000psi) making this a suitable pressure for MAW operations. Water flow for a 50micron diameter jet at 700bar is 2.5l/hr and abrasive flow rate less than 0.5Kg/hr.

Pumping options for MAWs include:

- For jet diameters less than about 50microns pneumatic intensifier pumps are an attractive low cost option and have been used for MAW development work. A plunger pump is located within a standard compact pneumatic cylinder to produce a pump with balanced loads. Standard pneumatic solenoid valves and sensors with a PLC can control the operation of two pumps in synchronous mode to provide a low pressure ripple water flow
- Above jet diameters of 50microns the poor efficiency of air driven intensifier pumps becomes an issue along with icing due to air expansion. A rotary cam (RC) pump is a suitable option. A prototype RC pump is currently being used for FAW developments that could be adapted to power MAWs
- Compact linear electrical drives are available that have the thrust and life cycle capabilities to power pumps for MAWs. The initial cost of linear electric drives is substantially more than for pneumatic drives but their operating costs are lower. Using linear drives would allow a completely electrically driven and controlled MAW cutting system to be developed.

5. FAW AND MAW OPERATING EXPERIENCE

Development work on MAWs has been reported in a number of papers (Miller 2002; 2003). The author originally set out to develop MAW systems for 40 to 60 micron jet diameters. These systems were subsequently developed to cut, drill and profile and to do this for extended periods of time. MAWs cut the wide range of materials as AWJs. Figure 3 shows examples of materials cut with 50 micron MAWs and Figure 4 shows a bench top MAW machining system with a 100 x 100 working area. Two important outcomes of the development work were the importance of abrasive quality control (Miller 2005) and the need for a suspension shut off-valve just upstream of a cutting nozzle that could be opened and closed many times per second to start and stop cutting (Miller 2004).

Figure 3 Sample materials cut with 50micron diameter jet – includes metals, polymers, glass and composites

Figure 4 Bench top MAW machining system

Work on MAWs has been put on hold for reasons associated with the need for an abrasive supply chain to provide quality assured abrasive in proprietary cartridges (Miller 2005).

A number of abrasive feed arrangements for FAW cutting heads have been investigated (Miller 2005). Figure 5 shows an abrasive mixture transportation pouch temporarily mounted on the X-axis of a cutting table and connected by a tube to a FAW cutting head. The pouch contains sufficient abrasive mixture for several hours cutting with a 90micron diameter jet.

Figure 5 90micron diameter FAW cutting head fed from a transportation poach

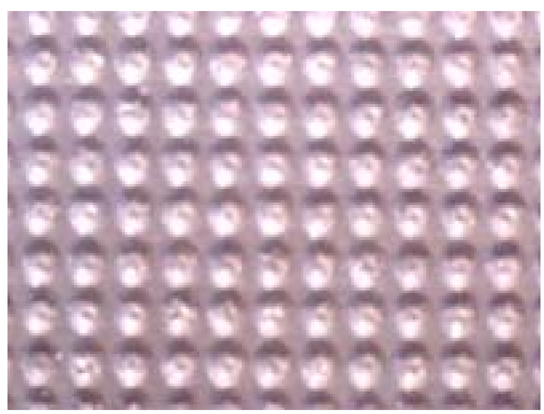

Figure 6 Surface features produced by a 90micron FAW jet at 4 features per second

The cutting head in Figure 5 has no valve between the pump and the cutting head. The author did not want to become involved in developing a UHP shut-off valve for which technologies already exist. Instead the pump was started and stopped to start and stop cutting. The FAW cutting head operated with a 35micron diameter waterjet and a 90micron diameter focus tube with a bore length of 3mm.

Cutting trials with FAW jets are at an early stage but, like MAWs, they appear to cut the same materials as AWJs. What is particularly interesting is the dynamic cutting capabilities of FAWs. Figure 6 shows surface features generated by starting and stopping the pump 4 times per second whilst moving the cutting head to produce surface features on a 250 x 250micron pitch in stainless steel. The dynamic response and accuracy of the cutting table used was poor and this probably had a significant effect on the elongated shape of what would be expected to be circular features. What is important is the control that is possible over the depth of features. Test work is required on producing blind holes, grooves and marking features on a wide range of substrates.

From trials carried out to date it can be concluded that FAWs have the potential to be used for dynamic machining. It should be noted that as components are miniaturised both feature size and material thickness decrease. As linear cutting speeds remain roughly constant the decrease in cutting time per component needs to be matched by a decrease in the time when a jet is not cutting material. The extreme is hole drilling in foil materials which an abrasive waterjet could drill at tens of holes per second. In practice the limit will be set by the waterjet on-off time.

Because FAWs and MAWs are dynamic cutting tools, relative to AWJs, there are more cutting parameters to be investigated than for AWJs. Extensive experimental work is required to understand and optimise FAW and MAW cutting capabilities.

6. DISCUSSION

It is interesting to speculate why the abrasive waterjet industry has not followed the laser industry in exploiting several different modes of generating cutting beams. Is it the complex technical, commercial and financial problems the leading AWJ companies encountered to achieve reliable and productive AWJs and build the abrasive waterjet market? Is it a lack of fluid dynamic knowledge of how cutting heads operate? To ask a company to repeat the experience of introducing a new abrasive waterjet technology, particularly when there are so many unknowns as to how cutting heads work, is probably a step too far.

In order to improve the chances of new abrasive waterjet generation modes being exploited the strategy the author is now following involves developing technologies that require the minimum changes to an AWJ system to convert it to a new mode of operation. This strategy is being followed for exploiting SAWs, FAWs and for high performance AWJ cutting heads. In particular the strategy:

- Minimises the technical and commercial risks to a licensee of introducing a new mode of abrasive waterjet operation
- Allows new capabilities to be retrofitted on to existing AWJ machining systems

- Increases the pool of companies that are in a position to license the technology for SAWs, FAWs and high performance AWJ cutting heads. An exploiting company need not manufacture complete AWJ systems and could already be selling abrasive feed systems and cutting heads.

The author is currently developing a SAW cutting head and abrasive feed system. The SAW abrasive feed system is also designed to allow trials of a new design of AWJ cutting head. The present state of developments on FAWs and MAWs is discussed in a companion paper (Miller 2005).

7. CONCLUSIONS

- A better understanding of the fluid mechanics of cutting heads provides the insight to extend the operating envelope of abrasive waterjets and to improve their cutting capabilities
- Statically suspending abrasive in a carrier fluid allows abrasive waterjets to operate as dynamic cutting tools with the potential of tens of events per second
- The dynamic capabilities of abrasive waterjets will open new applications in blind hole drilling, marking, surface texturing and in the machining of miniature components in foil materials
- The risks of introducing FAW and SAW technologies can be minimised by initially exploiting them as add on capabilities to AWJ systems
- AWJ cutting heads that utilise a new combination of flow processes have the potential to provide improved cutting performance.

8. REFERENCES

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