Abrasive-waterjet machining of most materials from macro to micro scales[§]

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Abstract

Since commercialized in the mid 1980s, abrasive-waterjet (AWJ) technology has been advanced remarkably. It has been elevated from a merely rough cutting tool to a precision machine tool. AWJ is inherently versatile and posseses both technological and manufacturing merits unmatchable by most machine tools. This paper addresses three of the top technological merits: (1) material independence, (2) wide range of part size and thickness, and (3) presevation of parent material properties. The manufacturing merits in terms of cost effectiveness and fast turnaround are also addressed.

Keywords: abrasive-waterjet, micromachining, delicate materials, material independence, preservation of material properties

1 INTRODUCTION

Abrasive-waterjet (AWJ) technology was commercialized in the mid-1980s. At that time, AWJ merely served as a rough cutting tool to take advantage of its material (type) indpendent property. Since then, the technology has advanced rapidly toward precision machining and user friendliness. OMAX Corporation was established in 1993 with the objective to make AWJ machining practical, affordable, and easy-to-use. This was accomplished by developing a patented "compute first - move later" conversational programming system built directly into the controls [1]; taking advantage of a PC-based CAD/CAM (LAYOUT/MAKE) to operate the AWJ process from design to machining of finished parts; and establishment of a robust and accurate traction drive system for precision machining.

The authors and his colleagues have actively participated in the SBIR/STTR program. Several novel processes were developed to advance the AWJ technology. Processes include AWJ piercing of delicate/brittle materials with weak tensile strength, micro AWJ (µAWJ) technology for meso-micro machining, AWJ 3D machining, improvement of AWJ cutting models, and others [2]. In particular, the success in developing and commercialization of the µAWJ technology has enbled AWJ to realize its potential as a versatile tool capable of machining most materials from macro to micro scales. Figure 1 illustrates photos of four AWJ-machined tweezers to show OMAX's progress in micro-machining.

Figure 1. Micromachining progress

AWJ technology possesses several technological and manufacturing merits unmatchable by most other tools [3].

- Material independence – machine most materials, homogenous and anisotropic, for a wide range of part size and thickness, from macro to micro scales
  - Metals, nonmetals, alloys, composites (with/without fiber-reinforced), laminates, and brittle materials (glass – partially tempered, and silicon wafers)
  - Most suitable for machining difficult materials such as hardened steel and titanium – a superior net-shaping tool
- Fast setup and programming – modern systems are operating with ease-of-use PC-based CAD/CAM embedded with advanced cutting model for automation
- A cold cutting process – no heat-affected-zone (HAZ)
- Amenable to 3D machining - a single tool for multiple machining processes including cutting, milling (etching), drilling, turning, beveling, and slotting, etc.
- No complex tooling required – cost effective and fast turnaround for R&D, prototyping, and production runs
- Negligible reactionary forces on parts
  - Simple fixturing
  - Machine large-aspect-ratio slots on thin materials without deformation (bending/warping)
- Part nesting to minimize material waste
- No hazardous waste byproducts

In this paper, the versatility of AWJ technology together with relevant AWJ-machined samples is presented. The objectives are to demonstrate the state-of-the-art of the AWJ technology while raising its awareness to the manufacturing community. It has been recognized that the lack of awareness of the technology has been a bottleneck to its growth as a versatile machine tool (http://www.frost.com/).

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2 AWJ TECHNOLOGY

2.1 Principle of Operation

A high-speed waterjet is formed by forcing pressurized tap water via a UHP pump up to 420 MPa (60,000 psi) through a small orifice. Abrasives are entrained into the jet through a feed port just downstream of the orifice where a vacuum is created (jet pump effect). The entrained abrasives are accelerated in a mixing tube attached downstream of the feed port. The diameter ratio of the orifice and the mixing tube is typically ranging from 1 : 2 to 1 : 3. The plungers in the pump are pushed into closed chambers to raise pressure and expel fluid through an outlet check valve; as the direction of the plunger is reversed, low-pressure fluid enters the chamber through an inlet check valve. OMAX offers the crank pump to drive the AWJ nozzle. It is known to be highly efficient (85%), low-noise (75 to 80 dba), and simple to maintain.

2.2 Facilities

Figure 2 illustrates drawings of a direct-drive crankshaft pump and an AWJ nozzle. There are two product lines of AWJ systems available, the OMAX and MAXIEM lines of JetMachining® Centers (JMCs), with a wide range of work envelopes and performance characteristics.[1] Accessories such as the Tilt-A-Jet, Rotary Axis and A-Jet are available for taper compensation and 3D machining.[2]

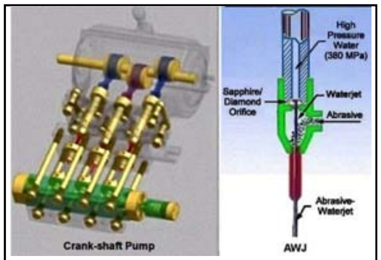


Figure 2. Crank-shaft pump and nozzle

Figure 3 illustrates the MicroMAX for precision meso-micro machining.[3] It has an X-Y cutting travel of 610 mm x 610 mm, a repeatability of ±2.5 µm, and a position accuracy of ±2.5 µm (Footnote #3). With the installation of the enclosure, the machine noise was reduced to nearly ambient level. By installing a set of HEPA filters on the exhaust of the enclosure, the machine could be qualified to operate in certain clean room environments. The MicroMAX is equipped with a 7/15 Mini MAXJET 5 nozzle with an orifice ID/mixing tube ID = 0.18 mm/0.38 mm, respectively. Also available is a beta 5/10 nozzle with orifice ID/mixing tube ID = 0.13 mm/0.25 mm.

Figure 3. MicroMAX JMC

The MicroMAX was the result of the commercialization of the µAWJ technology developed under the support of an NSF SBIR Phase II grant. A Phase IIB fund was recently awarded to match 50% of the revenue received from the sale of the MicroMAX.

3 AWJ-MACHINED SAMPLES

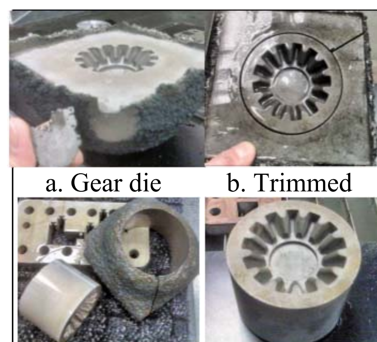
In this Section, several AWJ-machined samples are presented to demonstrate key technological and manufacturing merits of AWJ as a versatile machine tool [4].

3.1 Material Independence

As described in Section 1, AWJ is inherently material independent. The machineability, *M*, of many common engineering materials are defined through extensive cutting tests and incorporated into the PC-based CAD (MAKE). With all the other parameters kept unchanged, the smaller the *M*, the longer it takes to machine a part of the same grometry, dimensions, and edge quality. For example, the *M* for carbide (c2), SiC/SiC CMC, stainless steel, titanium, aluminum, glass, and polycarbonate are 0.1, 4, 81, 108, 216, 350, and 517, respectively. Note that AWJ cuts titanium 34% faster it cuts stainless steel. Figure 4 illustrates a collection of AWJ-machined miniature parts from a variety of materials.

Figure 4. Material independence

AWJ also cuts hardened and annealed steel at nearly the same speed. This is another advantage of AWJ over CNC hard tools. Figure 5 illustrates the use of AWJ to trim the overspray from a forged die (H13 at 56Rc). At such a hardened stage, the die is difficult to trim with EDM and the wire tends to break from time to time. It took AWJ only 1.24 hours compared to 7 to 8 hours with an DEM to trim the same part, with an estimated costs of $100 and $1000, respectively. The advantage of AWJ over EDM is clearly evident.


a. Gear die b. Trimmed
c. Overspray d. Core
Figure 5. trimming of gear die

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[1] http://www.omax.com/

[2] http://www.omax.com/waterjet-cutting-accessories/tilt-a-jet/61, http://www.omax.com/waterjet-cutting-accessories/rotary-axis/135, and http://www.omax.com/waterjet-cutting-accessories/a-jet/163

[3] http://www.omax.com/waterjet-cutting/machine/model/micromax

3.2 Part Thickness and Cold Cutting

Another inherent merit of AWJ is its capability of machining a wide range of part thickness by choosing a proper nozzle, the abrasive type, and abrasive feed rate. Figure 6 illustrates a photograph of a segment of an AWJ-cut 10-cm thick bisalloy gear section (top) for repairing a damaged wind turbine gear (bottom).[4] In fact, AWJ routinely cuts aluminum parts 20 mm thick with minimum taper. By using a miniature nozzle and fine abrasives, one could cut materials 0.1 mm and thinner. A high-density foam could serve to support thin and flimsy materials. The low reactionary force exerted by AWJ to the workpiece facilitates machining slots with large aspect ratios on thin materials, as illustrated in Figure 3. For example, AWJ was successfully applied to machine large-aspect-ratio slots on titanium sheets, used as micro flow channels for heat exchangers and reactors [5].

Figure 6. AWJ-cut wind turbine bisalloy gear segment

To demonstrate the AWJ advantage of cold cutting for a wide range of part thicknesses, tests were conducted to machine a pair of miniature tweezers and a butterfly from sheets of titanium (1.3 mm) and stainless steel (0.5 mm) with AWJ and a CO_2 laser. Figures 7 illustrates photographs of the AWJ- and laser-cut tweezers. It is evident that the AWJ cut part cleanly without any heat affected damage. However, the laser-cut counterpart displays serious heat damage in terms of discoloring, presence of slag (jet exit side), and warping. For the butterfly with a complex geometry, again AWJ cut the part cleanly, as illustrated in Figure 8. The excessve heat of the laser, visually evident from the image, simply vaporizes the the thin webs. Figures 7 and 8 clearly demonstrate the merit of preserving the integrity of parent materials by the AWJ. Although solid state lasers performs better than CO_2 lasers, the thickness limitation remains. Subsequently, wire (0.15 mm) EDM was used to machine the same tweezers. Althoguh the EDM-cut part is better in edge quality than the AWJ-cut one, the corresponding cutting times are 37 minutes and 45 seconds and 38 seconds, respectively. In other words, AWJ is nearly 60 times faster than wire-EDM.

Figure 7. AWJ- and laser-cut tweezers (courtesy MIT CBA)

Figure 8. AWJ/ laser-cut butterfly (courtesy MIT CBA)

[4] Refer to http://gear.epubxp.com/i/465232 for AWJ gear making

3.3 Delicate Materials

With conventional AWJ it is difficult to pierce delicate materials such as composites, laminates, glass, and silicon wafers where their tensile or adhesive strength is weak. During the initial piercing stage, the high-speed water entering the workpiece decelerates, stops, and reverses its course near the bottom of the blind hole (i.e., before breakthrough). As a result, most of the kinetic energy of the waterjet converts back to potential energy and a large stagnating pressure builds up inside the blind hole. The delicate materials would experience piercing damage in the form of delamination and microcracking when the stagnating pressure exceeds the tensile/adhesive strength of the materials [3]. This explains why AWJ has been mainly applied to machine external (e.g., trimming and cutting) rather than internal feaures (e.g., drilling holes and slots) of delicate materials, as there is no stagnating pressure buildup during external machining.

Considerable efforts were devoted to mitigate AWJ piercing damage to delicate materials. For example, the author had applied an abrasive cryogenic jet (ACJ) and a superheated AWJ or flash AWJ (FAWJ – patented [6]) to piere delicate materials without damage. Since most of working fluids in the ACJ and FAWJ evaporate upon exiting the nozzle, no damage will take place as there is no large buildup of stagnating pressure in the blind hole. Based on the above principle, parallel methods were developed successfully for AWJ machining of internal and external features in delicate materials (patents pending). Photographs of typical AWJ-machined internal (holes) and external (outside edges) features of several delicate materials are illustrated in Figures 9 and 10. Figure 9 illustrates a set of holes and characters machined on an 1.6 mm thick aircraft aluminum laminate, consisting of 30 0.05 mm thick thin sheets. The bonding strength of the adhesive is very weak and delamination would occur when the stagnating pressure inside the blind hole exceeds about 40 MPa. The sample in Figure 9 was machined by a novel process (patent pending). The AWJ-cut edges show no delamination when inspected under an microscope.

Figure 9. AWJ-cut internal/external features on aluminum laminate

Figure 10 illustrates photographs of AWJ-machine holes with several patterns on a thin piece of fiber-reinforced platics (FRP) and silicon wafer. The FRP is an anisotropic composite while the silicon wafer is a very brittle material, both with weak tensile strength. There is no observable delamination or cracking from the photograph.

3.4 Meso-Micro Machining

Considerable challenges were encountered during t he development of µAWJ tehnology. These challenges included the difficulties in fabricating mixing tubes with ID < 0.15 mm, overcoming high flow resistance in microfluidic supersonic 3-phase flow through small mixing tubes, feeding fine abrasives to achieve constant mass flow rate, and designing a supe rior platform for precision meso-micro machining. Multiple proprietary processes and appratus were subsequently developed to meet these challenges.

Figure 10. Internal/ external features on delicate materials

The commercialization of µAWJ technology has greatly broadened the AWJ applications toward precision micromachining. Using the production 7/15 and beta 5/10 nozzles, life-size orthopedic and prosthetic components were machined from titanium and stainless steel (Figure 11 [7]).

Figure 11. Orthopedic/prosthetic components

3.5 3D Machining

Two accessories are available for AWJ 3D machining. The Rotary Axis rotates about the x-axis and facilitates machining 2D-plus features on workpieces (e.g., the titanium mesh cage shown in Figure 11). The A-Jet ro tates up to ±60° from the vertical and enables machining 3D features such as bevels and countersinks (Figure 12). Complex 3D geometry could be made readily by com-bining the Rotary Axis and A-Jet. Figure 13 illustrates the AWJ-cut fish-mouth weld joint on steel pipes.

Figure 12. 45-deg bevels cut on steel plate and titanim honeycomb – Cut with A-Jet

4 SUMMARY AND FUTURE WORK

The commercialization of the µAWJ technology has elevateed AWJ as a high-value-added meso-micro machine tool. With its inherent versatility and recent technological advan-cement, AWJ technology has unleashed its potentials for machining most mate-rials from macro to m icro scales. Its technological and manufacturing merits are unmatchable by m ost machine tools, as dem onstrated by the AWJ-machined samples presented in this paper. There is no other single tool capable of machining so wide ranges of material, part size, and material thickness while preserving the integrity of parent materials. Therefore AWJ has bee n used extensively as a supe rior near-net shaping tool for extremely high precision parts. Under the support of the ongoing NSF SBIR Ph ase IIB fund ing, we continue innovating to advance µAWJ technology for precision 2D and 3D machining.


Figure 13. Fish- mouth joint – cut with both Rotary Axis and A-Jet

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