Recent Advancement in Abrasive Waterjet for Precision Multi-mode Machining

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Abstract

Abrasive waterjet (AWJ) has been demonstrated as a versatile tool that inherently possesses several technological and manufacturing merits unmatched by most machine tools. Among technological merits, AWJ is material independent and a cold cutting tool, capable of preserving the structural and chemical integrity of parent materials. The performance of waterjet has been elevated to the degree that it often competes on equal footing with conventional tools such as lasers, electronic discharge machining (EDM), and photochemical etching. For certain applications such as cutting heat-sensitive materials, AWJ is superior to thermal cutting tools such as lasers and electrode discharge machining. Furthermore in the absence of direct tool contact with the workpiece, AWJ mitigates several issues of heat and mechanical damage to composite materials and rapid wear of drill bits. AWJ produces no toxic byproduct and is more environmentally friendly than photo-chemical etching. The single-tool AWJ with accessories is qualified for multimode machining. Together with its cost effectiveness, fast turnaround, and user friendliness, AWJ is poised to be adopted broadly for stand-alone and near-net-shape machining. The versatility of AWJ is demonstrated through the presentation of a collection of AWJ-machined samples for various applications

1 INTRODUCTION

In the 2005 marketing report, Frost and Sullivan stated that waterjet machine tools emerged as the fastest growing segment of the overall machine tool industry in the last decade, and this trend is expected to continue.[3] The lack of awareness among the potential end-users, however, was posing a stiff challenge to the market participants on increasing end-user base. Since the publication of the Frost marketing report over a decade ago, waterjet technology has achieved significant advancement to take full advantage of its inherent merits. The performance of waterjet has been elevated to the degree that it often competes on equal footings with conventional tools such as lasers, electronic discharge machining (EDM), and photochemical etching. In certain cases, its performance greatly exceeds those of the conventional counterparts. The lack of awareness of the merits of waterjet technology and the latest advancements still present a bottleneck for its broad acceptance as a precision machine tool. The main goal of this paper is to demonstrate the versatility of waterjet for a wide range of applications to continue raising the awareness of the technology. In particular, with a single tool assisted with accessories, waterjet is capable of precision machining of 2D/3D parts from macro to micro scales with a wide range of part size and thickness for most materials.

A list of the technological and manufacturing merits of waterjet technology was given elsewhere [1]. Such merits have been fully taken advantage of in recent advancements of waterjet technology. Among the technological merits, waterjet is amenable to micromachining [2, 3]. Considerable efforts were devoted to the development of micro abrasive waterjet

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[3] (Frost and Sullivan – "The World Waterjet Cutting Tools Markets" Date Published: 30 Aug 2005 (www.frost.com)

(μAWJ) technology. For example, under the support of an NSF SBIR Phase II/IIB grant, OMAX developed and commercialized μAWJ technology, culminating the awarding winning MicroMAX® JetMachining Center® (JMC) [4].[4] As a cold cutting tool, waterjet induces no heat-affected zone (HAZ) on its cut edges. Unlike other thermo-based tools such as lasers, electronic discharge machining (EDM), and plasma cutters, waterjet preserves the structural and chemical properties of parent materials [5]. For very thin materials, the heat generated by CO_2 lasers and wire EDM often induces significant part warp, leaves considerable slag, and/or even vaporizes the material [4].

Another unique characteristics of waterjet is that it only exerts negligible impact and side forces on the workpiece. Combining both the low force exertion and cold cutting nature of waterjet, it enables machining very large aspect-ratio thin walls between features [5, 6, 7]. Such a unique capability is beyond those of the above tools as the heat induced thermal expansion of the thin wall results in considerable part damage including warping, edge hardening and burning, material vaporization. For heat sensitive materials, solid-state lasers pulsed at and wire EDM through multiple-pass machining have resolved a part of the above problem. Under such circumstances, solid state lasers and multi-pass wire EDM are at least 10 times slower than waterjet [5, 6]. The relatively large side forced exerted on the thin wall by the EDM wires is another unresolved issue. For parts with irregular features that require many piercing/drilling operations, the wire EDM process is considerably time consuming. Furthermore, waterjet does not produces hazardous byproducts and is superior to photochemical etching.

With the MicroMAX added to OMAX's product lines of JMCs, OMAX has established the full capability of precision multimode machining of most materials from macro to micro scales, namely the "7M" advantage, for a wide range of the part size and thickness [8]. Such capability can be readily put into practice as there are considerable flexibility in the specifications of our machines controlled by the Window-based Intelli-MAX software suite for automation. For example,

- Work envelopes – from 25 cm x 25 cm to 6.1 m x 4.0 m. Additional tank modules can be added to increase the length of the machine
- Position accuracies (repeatability) – from ± 0.127 mm (± 0.076 mm) to ± 15 μm (± 15 μm)
- Accessories available for machining nearly taper free parts and for precision 2D/3D machining

Extensive test cutting were conducted to demonstrate the versatility of waterjet in terms of its "7M" advantage. Selected samples are presented herein as a testimony the technological and manufacturing merits of waterjet for material-independent multimode machining.

2 TECHNICAL APPROACH

The advancement of waterjet technology has been focused on the development of software, hardware, and machining processes to take advantage of its technological and manufacturing merits. Such development has been made to automate the machining processes, improve machining precision and efficiency, and broaden its capability toward multimode machining for a broad range of applications.

- Software development

[4] The MicroMAX was named a Finalist of the 2016 R&D 100 Award (www.sbir.gov/node/1308555)

    - Upgrade periodically the Intelli-MAX software suite to add new machining features toward precision and automated 2D/3D machining
    - Upgrade new generations of cutting models to improve precision and optimize cutting performance
- Hardware development
    - Developed and commercialization of micro abrasive waterjet (μAWJ) for meso-micro machining
    - Developing novel fixtures for special applications
- Process development
    - Developed novel processes to feed fine abrasives for meso-micro machining
    - Developed cutting processes to mitigate piercing damage on delicate materials – composites, laminates, and brittle materials
    - Conducted cutting tests to demonstrate and improve the precision of multi-mode machining

3 FACILITIES AND TEST PROCEDURES

Much of the work presented in this paper was conducted at OMAX's Headquarters in Kent Washington. Relevant facilities and test procedures were presented in this section.

3.1 JetMachining Centers

AWJ machining was carried out in several models of JetMachining Centers (JMCs), including the MicroMAX and the Model 60120. The MicroMAX is one of the newest JMC developed and commercialized under the support of an NSF SBIR Phase II grant for precision meso-micro machining. With the NSF SBIR Phase IIB supplemental funding, the MicroMAX was upgraded to incorporate a Tilt-A-Jet (TAJ) for taper compensation and a Rotary Axis for beveling, countersinking, and other 3D features. The Model 60120 with a 3.4 m x 1.6 m cutting envelope was designed for machining relatively large parts. The largest JMC is the 160X-3 with a 14.2 m by 4.1 m cutting envelope. It was designed for machining very large parts. Photographs of the MicroMAX and 160X-3 are illustrated in Figure 1.

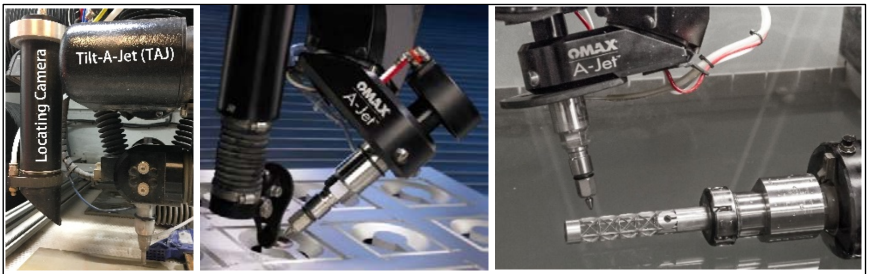
a. MicroMAX

b. 160X JMC

Figure 1. MicroMAX and Model 160X

Most of the JMCs are capable of accommodating the TAJ and two other optional accessories, a Rotary Axis for machining axisymmetric features, and an A-Jet (5-axis articulate head), as illustrated in Figure 2. The combined operation of the Rotary Axis and the A-Jet is capable of machining certain complex 3D features.

A camera is mounted next to the TAJ (Figure 2a) for precision locating and aligning features on workpieces. It was put in a water-resistant enclosure supplied with constant airflow to maintain slight positive pressure and prevent a moist microclimate from forming inside the enclosure over time. An automatic rinse system also installed to keep the lens cover free of debris/buildup for as long as possible.



a. TAJ b. A-Jet c. Rotary Axis

Figure 2. Accessories for 3D machining

3.2 AWJ Nozzles and Abrasives

Three standard AWJ nozzles 14/30, 10/21, 7/15 with orifice ID/mixing tube ID of .014" (.36 mm)/.030" (.76 mm), .01" (0. 25 mm)/.021" (.53 mm), .07" (.18 mm)/.015" (.38 mm), respectively. The 7/15 is the smallest production nozzle whereas the 5/10 nozzle (.005" (.13 mm)/.01" (.25 mm) that is a beta nozzle. A water-only-nozzle is available for cutting relatively soft materials. Figure 3 illustrates photographs of these nozzles. Garnet with sizes ranging from 80 to 320 mesh were used as the abrasives in this investigation to machine parts with a wide range of part size and thickness.

3.3 Software

The software for automating waterjet cutting is a PC-based Intelli-MAX® Software Suite. It includes a specialized CAD package LAYOUT, and a user friendly controller MAKE, and an OMAX Interactive Reference (OIR) (http://www.omax.com/waterjets/software).

Intelligent Software – The JMCs are controlled by a suite of software built around the patented motion control to automate the AWJ machining processes. Samples of the software suite are listed below.

Operational Software

- **Layout** - a full-featured CAD program created and designed to work with JMCs. Part drawings can be created by using a full set of drawing tools, importing a drawing from another CAD program in standard format such as DXF, and tracing a drawing or photograph. The toolpath of that part can then be created with **Layout**
- **Make** - actually controls the JMC to create parts with several simple steps: 1) open the toolpath file created by **Layout** (or another CAD/CAM drawing tool), 2) choose the material you want to use and the thickness (from which the exact nozzle motions required to make the part are calculated accurately to within 5/1000ths of an inch, and 3) click on the "Begin Machining" button and **Make** begins machining parts

Figure 3. Waterjet nozzles

Intelli-MAX® - a suite of new technologies integrated into the OMAX JMCs to enhance the performance of AWJ machining. It is designed to make higher tolerance parts faster - faster and with higher tolerance than any other AWJ systems. The suite has several software modules for part nesting, hole piercing, minimizing edge taper, and corner compensation.

3.4 Microscope

Micrographs of AWJ-cut parts were captured with a Leica stereomicroscope (Model M205C). It was equipped with a Leica DFC450 R2 Digital Cam & SW Kit for image capturing. Image analysis was performed using the Image-Pro Insight software developed by Media Cybernetics. It offers a wide range of tools for capturing and analyzing images.

3.5 Locating camera

A camera is mounted next to the TAJ (Figure 2a) for precision locating and aligning features on workpieces. It was put in a water-resistant enclosure supplied with constant airflow to maintain slight positive pressure and prevent a moist microclimate from forming inside the enclosure over time. There was an automatic rinse system to keep the lens cover free of debris/buildup for as long as possible.

4 RESULTS

In this section, we present the recent advancement in waterjet technology in terms of broadening its capability toward micromachining. With such added capability, waterjet has greatly broadened its machining applications from macro to micro scales for multimode machining of most materials – the "7M" advantage. Emphasis will be made to demonstrate the versatility of waterjet through presentation of samples of AWJ-cut parts with features that are difficult or even impossible to fabricate otherwise.

4.5 Recent advancement in waterjet technology

4.5.1 *Progresses toward micro machining*

Under the support of an NSF SBIR Phase II grant, OMAX developed and commercialized μAWJ technology, culminating the MicroMAX® JetMachining® Center for precision meso-micro machining.[5] The MicroMAX was subsequently upgraded to version II by incorporating the accessories of TAJ for temper compensation and of Rotary Axis for machining axisymmetric features on tubes and round stocks. The technological and design innovation of the MicroMAX had earned a Finalist of the 2016 R&D 100 Awards. OMAX subsequently received US Small Business Administration (SBA) 2016 Tibbetts Award. In the meantime, NSF selected OMAX as one of the success stories for its SBIR/STTR program as the result of the success in the commercialization of the MicroMAX and the excellent sales record (https://www.sbir.gov/node/1308555).

The MicroMAX takes advantages of most of the merits of waterjet technology described in Section 1. Success in making the MicroMAX available has greatly broadened the waterjet machining applications and boosted its market demand. With the capability of meso-micro precision machining, we have begun penetrating several industrial sectors in which conventional waterjets are inadequate for R&D, prototyping, and production applications. These sectors include but are not limited to aerospace, biomedical, electronic/optic, engineering, and military applications.

As a material independent and a cold machining tool, for cutting heat-sensitive materials, waterjet is particularly superior to thermos-based machine tools such as lasers, electric discharge machining (EDM), plasmas cutting and others. The heat generated by these tools

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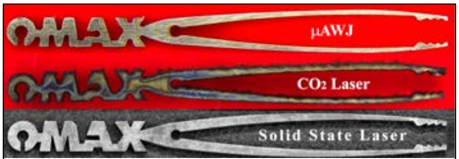
[5] There are five US patents and one PCT patent application pending for μAWJ technology

creates a heat-affected zone (HAZ) that alters the properties of the cut edges. For thin materials, the heat damage by CO_2 lasers result in considerable warping and residual slag or even vaporization of materials [1, 3]. Even for materials with high tolerance in heat damage, the HAZ must be removed or minimized. Removal often requires grinding that is time consuming whereas minimization of the HAZ requires significant reduction in cutting power and therefore cutting speed. Furthermore, the fact that waterjet exerts extremely low side force on workpieces facilitating it to machine very thin wall between features.

Figure 4. Progress toward AWJ micromachining - tweezers



a. Front view

b. Side view

c. Bottom view

Figure 5. Miniature stainless steel tweezers cut with CO_2 laser, μAWJ, and solid-state

Figure 4 illustrates photographs of selected AWJ-machined miniature tweezers made from stainless steel and titanium. The tweezers were machined with the AWJ nozzles as they become available commercially. The figure serves to demonstrate the recent progress toward AWJ micromachining as the nozzles are being downsized. One of the small tweezers were machined with a CO_2 and a solid start lasers and wire EDM at MIT's Center Bits and Atoms (CBA). Figure 5 illustrates high-resolution micrographs of the tweezers machined with the three tools. The tweezers CO_2 laser suffered considerable heat damage in the presence of serious warpage and discoloring together with a large amount of slag [5, 6]. On the other hand, the tweezers cut with the cold-cutting μAWJ induced not HAZ and preserved the structural and chemical properties of the parent material (stainless steel). Subsequently, a solid-state laser pulsed at 5 kHz was employed successfully to cut the tweezers. However, the times to cut the tweezers using the laser and μAWJ were 3 hours and 45 s, respectively. In other words, the μAWJ cut over two orders of magnitude faster than the solid state laser.

The tweezers were also machined successfully with the wire EDM using a 0.15-mm-diameter wire [5, 6]. The times to cut the tweezers using the wire EDM and μAWJ were 38 min and 32 s, respectively. The wire EDM cut 70 times slower than did the μAWJ.

The progress toward micro machining was further demonstrated in Figure 6 in which photographs of a set of AWJ-machined miniature butterflies on 0.5 mm thick stainless steel sheets are illustrated. The numbers next to the parts correspond to the span of the butterflies. The main difference between the tweezers and the butterflies was that the latter consisted of very thin walls between features. The combination of cold cutting and exertion of low side force on the workpiece by the AWJ is the key to cut the butterflies successfully. The thin walls between features presented considerably challenge to the CO_2 laser as the heat generated by the laser simply caused the materials on the thin walls to vaporize [5, 6].

The solid state laser was also used successfully to machine the butterfly with a span of 9.7 mm. The stainless steel sheet reduced from 0.5 mm to 0.25 mm. Figure 6 illustrates the photographs of the laser- and μAWJ-machined butterflies. There were many piercing operations in cutting the butterfly, which reduced the overall cutting speed of the μAWJ. The cutting times for the μAWJ and the laser were 2.2 minutes and about 60 minutes, respectively. The ratio of the cutting time was still nearly 30 times faster for the μAWJ than for the laser. Note that the focal spot of laser was 50 μm and the beam diameter of the μAWJ using the 5/10 nozzle was about 300 μm. As a result, the kerf width of the laser is considerably narrower than that of the μAWJ (Figures 5a, 7b, and 7c).

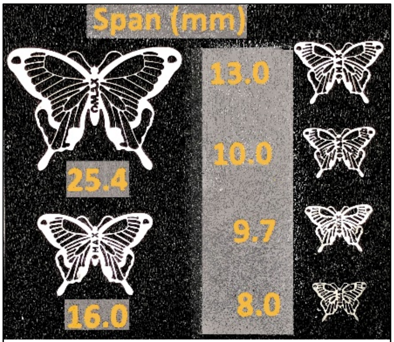


Figure 6. Progress toward AWJ micromachining – butterflies

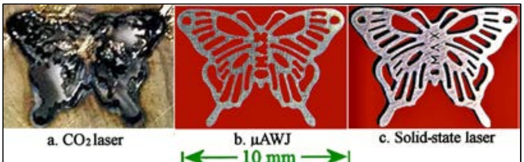


Figure 7. Stainless-steel butterflies cut with μAWJ and two lasers

There was no attempt to machine the butterfly with the wire EDM as there were many hole piercing operations required for cutting all the irregular internal features. Such operations would present considerable challenge to the EDM process as piercing must be accomplished with a different tool (e.g., EDM punching tool) and the wire must be restrung for each piercing.

4.5.2 *Material independence*

Material independence is another important merits for waterjet technology. While lasers and EDM cannot cut reflective and nonconductive materials, respectively, waterjet cut virtually most materials. The cutting model resided in the Window-based CAM, **Make**, consisted of a built-in lookup table of the machineability index, *M*, for common engineering materials [6]. The value of *M* was defined based on the results of extensive cutting tests; the value of *M* is proportional to the cutting speed for a given material. For example, *M* equals to 215 and 81 for aluminum and stainless steel, respectively. In other words, waterjet cuts aluminum 215/81 or 2.65 times faster than it cuts stainless steel for the same setup. Since erosion by the impact of high-speed abrasives is the primary mode of material removal, it behaves differently from cutting with CNC hard tools. As such, waterjet cuts titanium 34% faster than it cuts steel; it also cuts hardened steel nearly as fast as it cuts the annealed counterpart. The incorporation of the machineability index into the cutting model enabled waterjet as an automation machining process. In particular, the cutting model has been upgraded through the optimization of cutting processes and strategies to increase the cutting speed without degrading the cutting accuracy. Figure 8 illustrates the performance of three cutting models, Gen2 through Gen4. The diameter of the gear

corresponds to the cutting speed of individual cutting models for the same quality level. As such, the ratio of the cutting speed for Gen4 versus Gen2 and Gen3 are 1.87 and 2.15, respectively.

Figure 9 illustrates the photographs of a collection of various 2D/3D samples cut from a variety of materials consisted of a single element (metal, nonmetal, to anything in between), multiple elements (composites, laminates and alloys), and even nanomaterials with large gradients of nonlinear properties [6]. These materials possess a wide range of material properties: conductive, nonconductive, annealed, hardened, ductile, brittle, and fiber reinforced. Many of the samples were machined on the MicroMAX using the μAWJ nozzles. Descriptions of selected parts from the figure will be elaborated to demonstrate the versatility of waterjet technology.

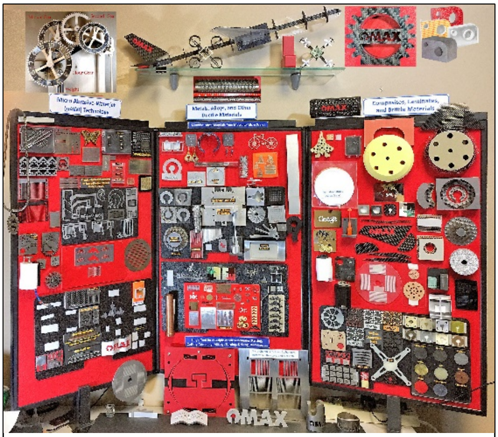


Figure 9. Photographs of AWJ-machined parts – an overview

4.5.3 *Biomedical applications*

The "7M" advantage of waterjet, particularly the capability of material independent meso-micro multimode machining, has demonstrated its versatility as a potential tool for a wide range of biomedical manufacturing [6, 9]. Many orthopedics and prosthetics, particularly implants, have b made from biocompatible metals such as titanium, stainless steel, Inconel, nitinol, and others. Figure 10 illustrates a collection of metal orthopedic components including several forms of mini plates for implant fixation. The 5/10 nozzle together with 320 mesh garnet was used.

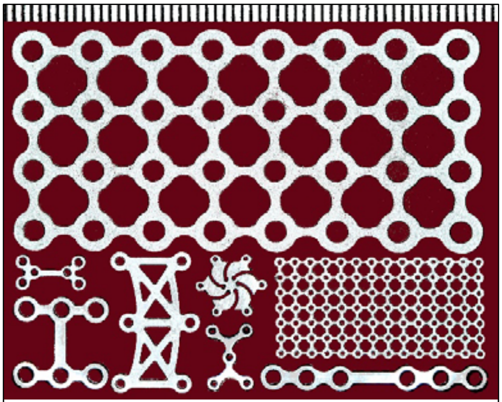


Figure 10. μAWJ-machined metal orthopedic components

For machining 3D orthopedics and prosthetics, the Rotary Axis, the A-Jet, and/or the combination of the two can be used. Figure 11 illustrates photographs of AWJ-cut diamond shaped holes drilled on a stainless steel plate (Figure 11a) and a 6 mm OD titanium tube (Figure 11b). The titanium tube with the shaped holes is called titanium mesh cage TMC) that is used in spine surgery [10]. The TMC is a rigid structure that does not amenable to bending about its axis. An alternate design with an interlocking link would have the built-in flexibility about as well as stretchable along its axis. Such interlocking features can be readily machined with the aid of the Rotary Axis, such as the one illustrated in Figure 11c.

Composites such as carbon fibers and ultrahigh molecular weight polyethylene (UHMW) have been used extensively for many years in engineering and aerospace manufacturing to take advantage of their excellent Strength to weight ratio. They were subsequently adopted for fabricating prosthetics for exterior fixation. Waterjet has been applied to machined biomedical components for all these materials [6]. Figure 12 illustrates two carbon fiber knee braces machined with waterjet. 2D Carbon fiber components were first machined with waterjet and then thermally formed to their final shapes. For implants and internal fixation component, only few composites are biocompatibility and contamination free. One such composites is Poly-Ether-Ether-Keystone (PEEK) originally launched by Victrex® in 1998 and marketed as PEEK-OPTIMMA™. Extensive laboratory and clinical tests have shown the superiority of PEEK to metals and UHMW as implant materials [11].

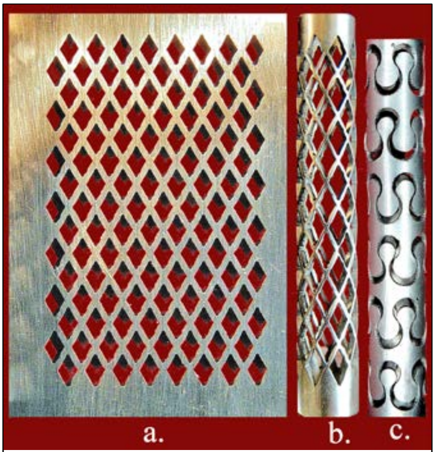


Figure 11. μAWJ-machined Titanium mesh cage and interlocking link

- The chemical structure of polyaromatic ketones confers stability at high temperatures (exceeding 300°C)
- Resistance to chemical and radiation damage
- Compatibility with many reinforcing agents (such as glass and carbon fibers)
- Greater strength (on a per mass basis) than many metals
- Compatibility with modern medical imaging techniques (i.e., no shadows in X-ray, CT or MRI images) for monitoring the healing process


Figure 12. Two AWJ-machined carbon fiber knee braces

The primary author has been conducting AWJ cutting tests of prosthetic and orthopedic components using PEEK materials supplied by Victrex and Invibio. One of the popular implants made from PEEK is the cranial implant that must be sized optimized to fit individual patients of all ages from infants to adults. Figure 13 illustrates samples of AWJ-machined PEEK cranial implants with a thickness of 3.2 mm. The samples were machined in 2D and then thermally shaped to a 3D form of a spherical segment. Such implants can be fabricated in several hours including secondary processes to prepare them for meeting the FDA requirements. Note that the field deployability of a mobile waterjet system has been successfully demonstrated for rapid


a. Unfilled b. Filled

Figure 13. μAWJ-machined PEEK cranial implants thermally shaped to 3D form

response repair in battlefields.[6] The combination of cost effectiveness, fast turnaround, and field deployability would enable waterjet to fabricate patient specific implants in remote areas where supplies are scarce and timely shipment from manufacturers is not an option. Now that portable waterjet systems are commercially available, they would have a great potential for remote biomedical manufacturing and could play an important role for emergency rescue missions.[7]

4.5.4 *Nearly taper free parts*

Abrasive waterjet spread as it exits the nozzle exit. Its cutting power reduces with the increase in the depth of cut. As a result, the AWJ-cut edge displays a nature taper in response to the reduction of cutting power with the depth of cut. The taper reduces with the decrease in the cutting speed but the angle cannot be controlled accurately. The TAJ was designed to tilt the cutting head dynamically to compensate for the taper on the part edges while leaving twice the taper on the scrap. The TAJ is therefore capable of machining virtually taper free edge without the sacrifice of the cutting speed [12].

The μAWJ together with the TAJ was applied to machine several examples to demonstrate the capability of cutting parts with square edges. Examples included sets of miniature planetary and cycloidal gears that were assembled to form gear chains driven by micro motors and novel devices that were otherwise too challenging for existing machine tools [4, 8, 12]:

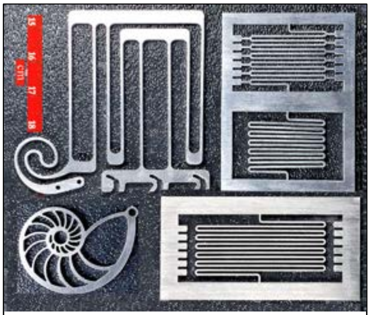


Figure 14. μAWJ-machined flexures for microsplines - Courtesy of NASA/JPL

- Nonlinear load cells consisted of large-aspect-ratio flexures with constant or tapered cross-sections. The patented load cells was designed and confirmed to have five orders of magnitude force range [13]
- Aluminum flexures and relevant components served as the key elements of microsplines of prototype asteroid gripping device under development at NASA/JPL for Asteroid Redirection Mission (ARM) program, as illustrated in Figure 14. The spring-like flexures, 3.2 mm thick and 0.5 mm wide, are linked to the frame at two locations as the support. They are extremely delicate to machine

Both the load cells and the grippers require thin flexures with large aspect ratio and square edge to achieve the maximum sensitivity. Waterjet is a cold cutting tool that exerts negligible side force on the workpiece. When the TAJ is activated to minimize the edge taper, waterjet is advantageous over most traditional tools for machining such flexures. For mechanically and thermally based tools, the limits on the aspect ratio of flexures depend on the amount of side force exertion and/or heat generation, respectively. For example, solid state lasers must pulse at high frequency and wire EDM must use very thin wire to minimize or mitigate heat distortion of thin flexures, resulting in more than 10 times in the reduction of cutting speeds [4, 8]. The cost ratio of the applying wire EDM and waterjet to cut the flexures was 14 to 1, leading to a cost saving of 93%!

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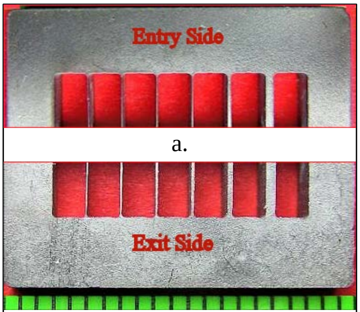
[6] http://sme.org/MEMagazine/Article.aspx?id=78461
[7] https://www.protomax.com/

Figure 15 illustrates a μAWJ-machined titanium part with several slots separated by thin walls of different width, 0.05, 0.076, 0.1, 0.25, 0.5 mm, respectively. The thin walls that were machined with the TAJ activated are essentially straight with negligible distortion in the absence of HAZ and very low exertion of side force.



a.

b.

Figure 15. μAWJ-machined titanium part with nearly taper free thin walls

4.5.5 *3D machining*

For operational safety consideration, waterjet is basically a 2D machining tool. There are however several methods to fabricate 3D parts using 2D waterjet systems [14]. One of such methods is to machine the part multiple times at different orientations [??]. Another method is to cut a set of 2D components and then assemble the components into a 3D part. Yet another method is to cut a part in 2D and then shape the parts into 3D form via secondary processes (e.g., folding, layering, and thermal shaping).

With the aids of multi-axis accessories such as the TAJ, Rotary Axis, and A-Jet (Figure 2), a 2D waterjet platform is transferred into a 3D counterpart. The TAJ was designed to compensate for edge taper to machine nearly taper free parts. The Rotary Axis and A-Jet were designed to machine axisymmetric parts on tubes and rods and bevels and countersinks. For example, the titanium mesh cage and the interlocking link shown in Figure 11 were machined with the Rotary Axis.

The rotation of the Rotary Axis or the tilting of the A-Jet are controlled by a software algorithm that lets one input "extra" data, called XData, for any entity in a drawing or tool path. In essence the tool path of the part is drawn in 2D. By adding an XData note onto a tool path, the Y-axis is turned into a rotational axis for the Rotary Axis or a tilting axis for the A-Jet. An example of cutting a countersink hole using XData is demonstrated in Figure 16. Figure 16a display the 2D tool path of two trepanning holes. By inserting an XData note “Start Beveling at 37 deg.” onto the outer circular tool path, the CAM program **MAKE** is commanded cutting a countersink feature by tilting the A-Jet at an angle of 37 degrees about the vertical axis while executing the trepanning operation. Figure 16b presents a 3D view of the countersink tool path. The photographs of the top and bottom countersink hole machined on a phenolic plate are shown in Figure 16c and 16d, respectively. Figure 16e illustrates the micrograph of the hole sectioned along its centerline. Note that Phenolic is a composite with relatively weak tensile strength. Low pressure waterjet piercing was employed to mitigate delamination.

a. 2D tool path	b. 3D tool path	c. Top view	d. Bottom view	e. Sectioned side view

Figure 16. AWJ-machined phenolic countersink hole using XData

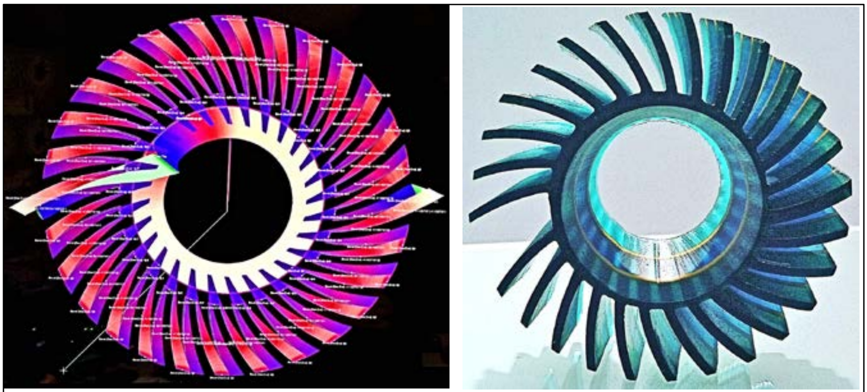
By combining the Rotary Axis and A-Jet, machining operations such as turning, facing, beveling, countersinking, grooving, drilling (angled and shaped holes) can be readily performed. As such 3D parts with complex geometry can be machined. One of the examples is a "fish mouth" weld joint machined with the combined operation of the Rotary Axis and the A-Jet, as illustrated in Figure 17. Figures 17a and 17b show two views of the weld joint. Figure 17c illustrates the assembly of two aluminum tubes joined together via the weld joint. Note that the features on one of the tubes were machined with only the Rotary Axis but not the A-Jet

Figure 17. AWJ-cut "fish mouth" weld joints using combined operation of Rotary Axis and A-Jet

For manufacturing very large structures such as spherical pressure vessels, the tank walls are often constructed by welding spherical shells together. The weld joints were often cut with plasmas torches. There is considerable damage on the plasmas-cut edges that must be removed as a part of the weld preparation process. The damaged layers are often removed by hand grinding that is not only time consuming and labor intensive but also inaccurate. The combined operation of the two accessories would offer an excellent process for weld preparation of large pressure vessels. Not only the profile of the weld joints can be machined accurately but also there is no damage layer of HAZ to remove.

4.5.6 ***Glass art pieces and jewelries***

The versatility of waterjet has been taken advantage for cutting glass art pieces and jewelries [15]. Figure 18 illustrates the tool path and a photograph of a glass rotor made from a soda lime manufactured by Bullseye Glass Company in Portland, Oregon, USA. It was used because the glass color sheets are compatible with one another allowing them to be cast together into a block. Figure 18a is the tool path overlaid with XData to convert the 2D paths into a 3D counterpart enabling the control of the A-Jet to cut the 3D rotor blades. Cutting the brittle glass rotor was a very delicate and risky operation. It often required dif-



a. Tool paths with Xdata embedded b. AWJ-machined glass rotor

Figure 18. AWJ machining of glass rotor with the A-Jet

ferent programming for cutting metal counterpart. For example, it was critical how the material was held in place and the order and priority of cutting. Most work was cut sitting on a surface till to reduce the residual wastes falling away. Other consideration was the type of form generated as “TAPER LOCK” can trap the form within the waste material. Furthermore residual stress within the material can cause internal fracturing especially in thicker glass material. The degree of difficult in cutting the glass rotor is reflected from the presence of an imperfection in Figure 18b with one of the blades broke away while machining the part.

Another example was to cut glass medals with waterjet demonstrating the capability of reproducing delicate handwriting [16]. It served to explore how waterjet can capture one’s handwriting accurately. Figure 19 illustrates such a medal cut from the black soda-lime glass by Bullseye. The work became a piece called “Chitter Chatter” exhibited at Crafts in the Bay, Cardiff, Wales and collect 2017. London to an International audience. It was subsequently exhibited as "Chatter iteration 2” at the National Glass Centre Sunderland UK (February 10th - April1 5th 2018).[8]

Figure 19. AWJ-cut medal on black soda lime glass

Waterjet has also be applied to jewelry making. Figure 20 illustrates photographs of a waterjet-cut necklace and several ear rings. The main metal used in these jewelries is niobium that changes into a spectrum of brilliant color by anodizing it at different voltages. The pieces were machined in 2D and then mechanically formed into their final shapes.

Figure 20. AWJ-machined necklaces and ear rings (Courtesy of Holly Yashi**)**

4.5.7 *Model building*

The versatile waterjet has been broadly applied for building a variety of models by the novelists and professionals. Model builders embrace waterjet because of the “7M” advantage together with user friendliness, cost effectiveness, and fast turnaround. In particular, waterjet can be used in all stages of development from design, prototyping, to production. Waterjet has been a popular tool for use in high schools and universities to build robots, model cars (RC, electric, and solar) for competition and racing.[9]

[8] Both developed through Creative Wales funding from Arts Council Wales.

[9] https://www.omax.com/news/customer-successes/talented-local-students-collaborate-omax-corporation; https://www.omax.com/news/customer-successes/ubc-mentors-generations-waterjet-savvy-

Figure 21 illustrates AWJ-machined two quadrones with a carbon fiber frame and ducts. Figure 21a corresponded to the result of the initial attempt to build the quadrone consisting of four cylindrical carbon fiber ducts. It turned out that the cylindrical ducts were too heavy for the propellers to lift the quadrone. Subsequently, several iterations were made to reduce the weight of the drone. Finally the cylindrical ducts were lightweighted by shortening their length while cutting away 5/6 of their duct perimeters, as illustrated in Figure 21b. The thrust generated by the propellers was then sufficient to fly the lightweighted drone. The above exercise is intended to demonstrate the advantage of using waterjet for model building and optimization.

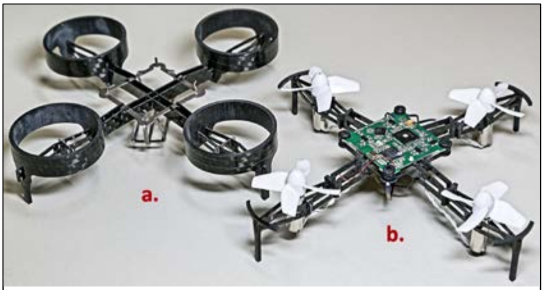


Figure 21. AWJ-machined carbon fiber quadrones

5. SUMMARY

With the award winning MicroMAX added to OMAX's product lines of waterjet systems, a full capability has been established for multimode machining of most material materials from macro to micro scales (that is, the "7M" advantage). Such versatility together with several technological and manufacturing merits inherent to waterjet technology cannot be matched by most machine tools. Technological merits include material independence, cold cutting, negligible exertion of side force on workpieces, and micromachining capability, whereas manufacturing merits include low capital and operating costs, fast turnaround, user and environmental friendliness, and field deployability. In addition to OMAX, waterjet has been employed extensively and favorably in production lines of manufacturers.[10] A collection of waterjet machined samples for a wide range of applications were presented to demonstrate the versatility of waterjet technology. Our goals are to raise the awareness of waterjet for advanced manufacturing and to broaden the applications for R&D, prototyping, and production. In particular, the versatile waterjet has begun penetrating into the high-value-added machining market across the entire manufacturing sectors for aerospace, microelectronic, and biomedical applications. There are considerable room for deploying waterjet in the above market. Raising the awareness of waterjet is the key to accelerate the rate of penetration.

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engineering-students; https://www.omax.com/news/customer-successes/ubc-mentors-generations-waterjet-savvy-engineering-students

[10] http://www.sme.org/uploadedFiles/Publications/ME_Magazine/2011/November_2011/November%202011%20f3%20Waterjet.pdf

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