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Paper

μAWJ Technology for Meso-Micro Machining

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ABSTRACT

Waterjet technology has technological and manufacturing merits that cannot be matched by most established machine tools. There is considerable demand for downsizing beam diameters of abrasive-waterjets (AWJs) to reduce costs for machining of various microproducts. Current production AWJ systems are limited to cutting features around 200 to 300 μm due to difficulties in further downsizing AWJ nozzles. Although waterjets with beam diameters 25 μm or finer have been in use for cutting a limited set of soft materials, it is the AWJ that is difficult to downsize below 200 μm. First of all, the three-phase slurry inside the mixing tube gradually shifts from gravity to capillary dominated flow as the beam diameter of AWJ reduces below 200 μm. In addition, the size of abrasives must reduce accordingly to prevent clogging of miniature mixing tubes resulting from bridging of large particles. The changes in the flow characteristics and flowability of very fine abrasives are most challenging toward nozzle downsizing. Funded by two NSF SBIR grants, OMAX has demonstrated the feasibility of downsizing AWJ nozzles for machining 100 to 50 μm features. Prototypes μAWJ systems are under development. Preliminary results are presented through demonstrating sample parts machined with experimental μAWJ nozzles.

1. Introduction

Driven by the developments and commercialization of micro-electro-mechanical-systems (MEMS) and subsequently nanotechnology with capability of fabricating a variety of microsystems, previously cost-prohibitive or technologically unattainable devices can now be cost-effectively fabricated with precision. New applications are being introduced daily, resulting in explosive growth in demand for the products that employ them. Similarly, the ability to fabricate precision metal, nonmetal, and composite materials with a scalable machining process provides designers and engineers with the cost-effective solutions they need to develop high-performance, miniaturized devices. Lasers, ultrasonic machining, EDM, photochemical etching are among those scalable machining processes. In order to bring microproducts into the market place, there is considerable demand for versatile and cost-effective machining processes.

Waterjet technology has come a long way from merely being a rough cutting tool to a versatile precision machine tool (Liu et al., 2010). It is the versatility of the emerging technology in terms of technological and manufacturing merits that cannot matched by most established machining technology (http://www.streamlinemachinesource.com/WATERJETADVANTAGES.PDF). Most importantly, waterjet technology is amenable to machining by downsizing the nozzles together with the use of fine abrasives. Current state-of-the-art limits the AWJ nozzles for machining features greater than 200 μm. Only recently, novel processes have been developed to allow further downsizing AWJ nozzles with beam diameters below 200 μm. In parallel, low-power and low-flowrate high-pressure pump must be developed to drive the μAWJ nozzles efficiently and cost effectively. Precision XY traverse and platform to match the cutting accuracy of μAWJ nozzles must also be designed for optimum performance.

Technological and manufacturing merits of waterjet technology are described in detail in the link given above. Those merits that are relevant to meso-micro machining are given below:

- Technological merits – from macro to micro machining for most materials (“5M”)
    - Material independence – a single tool that cut most materials according to its machinability, as opposed to established machine tools that are material selective
        - Most engineering materials (acrylic, Teflon, plastics, rubber, wood, and others)
        - Ductile and brittle materials (e.g., steel –hardened or not, titanium, alloy, ceramics, glass, stone, and many others)
        - Delicate materials (silicon, laminates, and composites, etc.)
    - PC-based CAD/CAM automation
    - Ability to cut parts with a wide range of thickness and nearly taperless
    - Cold cutting without inducing heat affected zones
    - Low force exerting to workpieces - capable of machining very large aspect-ratio slots and ribs on thin shims (Liu et al., 2008)
    - Amenable to multimode of machining with a single tool of AWJ nozzles – piercing, cutting, turning, trimming, milling, beveling, and others
- Manufacturing merits
    - User friendliness – no steep learning curve for operations and maintenance

- Fast turnaround – capable of machining a part from design to finish in minutes to hours
  - Simple fixturing – fast setup
  - No tooling required – cost effective for machining small and large lots
  - Multiple input modes of part drawing
- Most suitable as a versatile and low-cost machine tool
  - No secondary process required for most nonessential parts
  - Used favorably as a net-shape tool when extreme precision is required particularly for cutting parts from hardened alloys to increase productivity, save costs, and minimize breakage of conventional tools

The fast turnaround and cost effectiveness of waterjet technology have in fact helped many jobshops and machine shops save their jobs from shipping abroad. Large manufacturers have begun recognizing such benefits as shipping jobs abroad would considerably lengthen the turnaround time particularly for jobs that require significant amount of interactions. In the midst of the worst economic downturn since the Great Depression, there is a growing belief that offshoring of U.S.-based jobs is rapidly reaching a plateau and that "onshoring" — the repatriation back to the United States of some of that overseas investment — may become more frequent. With the industrial acceptance of waterjet technology growing rapidly, it is expected to play an important role in the welcomed trend reversal that would help gradually regain our leadership in manufacturing.

The "5M" of waterjet technology indicates that it has potential for further downsizing toward meso-micro machining. Considerable efforts have been made in the last two decades to reduce the beam diameter of AWJs in an attempt to approach that of lasers (Miller, 2005 and 2006). Although research results have shown promising results that the beam diameter of AWJs could be downsized for meso-micro machining, considerable challenges must be overcome in order to develop µAWJ systems to be deployed reliably for production. Although the beam diameter of water-only jets can be downsized to 25 µm and smaller, they could only be used to machine small features in relatively soft materials. It is the AWJ nozzle that must be downsized for meso-micro machining. Currently, commercial AWJ systems are limited to machine small features around 200 to 300 µm (http://www.sme.org/cgi-bin/find-articles.pl?&ME09ART48&ME&20091101&&SME&#article).

Since abrasive-waterjet machining is achieved by the contribution of many individual abrasive particles performing micromachining, abrasive-waterjets are amendable for micromachining by using fine abrasives and downsizing the nozzles to minimize the beam diameter of the jet in which the abrasives are confined. As the mixing tube diameter reduces below 200 µm, the three-phase slurry moving through the mixing tube gradually shifts from gravity to capillary dominated flow. First of all, the resistance of the slurry flowing through the mixing tube increases as its diameter decreases. In addition, the size of abrasives must reduce accordingly to prevent clogging of miniature mixing tubes resulting from bridging of two large particles.

Therefore, the change in the flow Characteristics and the entrainment and flow of very fine abrasives present the most challenges to further downsize AWJs. There are several key challenges that must be overcome:

- The alignment between the orifice and the mixing tube becomes increasingly important as the nozzle continues shrinking in order to minimize the flow resistance.
- For a capillary dominated flow, as a result of the meniscus effect, a column of water remains inside the bore of the mixing tube after the jet is turned off. The height of the water column is

inversely proportional to the mixing tube diameter. A backsplash results when the relatively low-speed front of the waterjet, as soon as it is turned on, impinges on the meniscus surface of the water column. The backsplash would wet the residue abrasives inside the mixing chamber and in the feed port entrance. As the wet abrasives accumulated in these areas after many on-off cycles, the passage of abrasives fed from the hopper into the nozzle reduces continuously, resulting in reduction in the abrasive flow rate that governs the cutting speed and quality. The feed tube is clogged by wet abrasives when the passage becomes too narrow to allow dry abrasives to flow through.

- The size of abrasives must reduce with the diameter of the mixing tube. It is well known that very fine abrasives do not flow well under gravity feed – poor flowability. As such, the flow rate of the abrasives would be intermittent, resulting in poor cut quality in the form of nonuniform kerf width or even skipped cut. In addition, fine abrasives tends to clump or coagulate together to form loose lumps, particularly when they absorb moisture in high humidity areas or are subject to charge by static electricity.

OMAX has been awarded two NSF SBIR grants (Phase I and II) to develop μAWJ technology by developing novel processes and hardware to downsize AWJ nozzle for meso-micro machining. During Phase I experimental μAWJ nozzles, auxiliary devices, and processes for improving feeding of fine abrasives were designed, assembled, and tested. The nozzles were applied to machine small features in thin materials such as holes and slots that appear in components for biomedical, MEMS, and green energy production applications to take advantage of the technological and manufacturing merits of waterjet technology. As a part of the commercialization effort, a 5-10 miniature nozzle with IDs of the orifice and mixing tube at 0.005" (130 μm) and 0.01" (250 μm), respectively, were under beta testing.

For the SBIR program, OMAX has established collaboration with research institutes such as Microproducts Breakthrough Institute (co-established by Pacific Northwest National Laboratory and Oregon State University), Massachusetts Institute of Technology, University of Washington, and Ryerson University. GE Global Research, Velocys, and others serve as industrial collaborators to the development of μAWJ technology.

1. Technical Objectives

The overall technical objective of this paper was to demonstrate the feasibility of downsizing AWJ nozzles toward meso-micro machining. Technological and manufacturing merits of waterjet technology and its most recent advancements have demonstrated abrasive-waterjet's capabilities for a broad range of machining applications. On a local scale, the nature of AWJ machining pertains to contribution by individual abrasive particles performing micromachining. On a global scale, the abrasives confined in the beam diameter of AWJs define the kerf width of the machine features. For meso-micro machining, the beam diameter of AWJs must be downsized to satisfy the criteria of micro-meso scale of interest. Current AWJ technology limits the minimum the size of machined features to about 200 to 300 μm. Further downsize of AWJ nozzles presents considerable challenges to overcome difficulties encountered as the slurry changes from gravity to capillary dominated flow Characteristics and the deterioration of flowability of fine abrasives. Supported by NSF SBIR Phase I and II grants, novel hardware and processes were developed to meet the above challenges. Our objectives are to develop μAWJ nozzles capable of machining features around 50 to 100 μm. Preliminary results of recent efforts in downsizing nozzles toward meso-micro machining are presented to demonstrate the feasibility of fulfilling the technical objectives. Prototypes of μAWJ nozzles are being developed and tested during Phase II R&D.

2. Technical Approach and Facilities

3.1 Technical approach

Under the support of two NSF SBIR Phase II grants, several miniaturized experimental nozzles, auxiliary devices, and novel processes for uniform feeding of fine abrasives into the nozzles were developed and tested. The nozzles were downsized from the smallest production 7-15 nozzle. Auxiliary devices were developed as attachment to production nozzles to reduce the kerf width of cuts. Novel processes were developed to improve flowability of fine abrasives and mitigate clumping or coagulation of particles that would lead to nozzle clogging. The experimental nozzles and auxiliary devices were mounted on one of OMAX's JetMachining Centers® for testing its functionality and cutting performance. Functionality tests were conducted to determine the beam diameter and the quality of AWJs generated by experimental nozzles and the uniformity and steadiness of feeding of fine abrasives. Cutting performance of the nozzles and auxiliary devices was evaluated by using coupons of various materials and cutting patterns selected or furnished by our collaborators. Selected AWJ-cut specimens with potential practical applications are illustrated in Section 4. In addition to visual inspection of the AWJ-cut specimens, measurements were made from micrographs to quantify the test-cut results.

3.2 Test facilities

3.2.1 *JetMachining® Centers and nozzles*

Machining tests were conducted using one of OMAX's JetMachining® Centers (JMC), Model 2652 or 2626.[1,2] Figure 1a illustrates a photograph of the Model 2652 JMC. There are a collection of accessories available for machining special features using AWJs. One of accessories is the Rotary Axis, a robust waterproof rotary head allowing the waterjet to cut axisymmetric features.[3] Tests of meso-micro machining were conducted using three nozzles, one production nozzle (7-15 nozzle) and two experimental nozzles. One of the experimental nozzles (5-10 nozzle) is currently under beta testing. The orifice and mixing tube diameters, water flow rates, and abrasive mass flow rates for these nozzles are listed in Table 1. Typical pump pressures were between 345 to 380 MPa. Abrasives were gravity fed from the hopper via a feed tube connected to the feed port of the nozzle body. Figure 2 illustrates photographs of the 7-15 nozzle. The 5-10 and R&D nozzles share the same body of the 7-15 nozzle. Novel processes have been developed to operate these nozzles without vacuum assist and water flushing.[4] .

Table 1. Abrasive-waterjet nozzle dimensions and flow rates

Nozzles	Orifice Diameter (mm)	Mixing Tube ID (mm)	Water Flow Rate (l/min)	Abrasive Flow Rate (kg/min)	Abrasive Size (mesh)
7-15 Mini MAXJET 5	0.18	0.38	0.79	0.08	220
5-10 Nozzle (Beta)	0.13	0.25	0.4	0.04	220/320
R&D Nozzle	0.09	0.22	0.2	0.03	320

1 http://www.omax.com/machine_details.php?product=2652
2 http://www.omax.com/waterjet-cutting-machines/model-2626.php
3 http://www.omax.com/accessories-rotary-axis.php
4 Patent pending (2010).

3.3 CAD/CAM programs

OMAX's PC-based CAD program, LAYOUT, was used to draw from scratch or imported from AUTOCAD drawings of patterns to be machined with the nozzles. The patterns were subsequently converted into tool paths according to various parameters pertaining to those of the workpiece (material types and thickness), of the abrasive-waterjet (pressure and nozzles), of the abrasives (type, mesh, and mass flow rate), and of cut qualities (from Q1 through Q5) (Liu et al, 2009). The LAYOUT then passes an executable file to the CAM program, MAKE, for automated machining of the parts. New software programs to control the operations of the suite of hardware accessories, established or newly developed, are being developed and will eventually be incorporated into future versions of the Intelli-MAX software.[5]

4. Test Results

The development of µAWJ technology would fill the need for a versatile and low-cost micromanufacturing tool for a wide range of industrial and military applications in biomedical, microelectronics, green energy, and other fields. Our target is to develop µAWJ systems by downsizing AWJ nozzles for meso-micro machining. R&D nozzles and auxiliary devices were developed and applied to machine features in thin materials such as holes and slots around 100 µm.

Through the collaboration with academic institutes and manufacturers, typical components for the above applications were machined with miniature R&D nozzles together with novel auxiliary devices. Our collaborators usually furnished materials and drawings of machining features to us for testing. They then inspected the test results and provided us with feedback.

4.1 Basic features

The R&D nozzles and auxiliary devices were used to pierce holes and machine slots to demonstrate their ability to machine very small features. For these tests, emphasis is made to determine the smallest features we could machine with these nozzles with and without auxiliary devices. No attempt was made to perfect the piercing/machining processes to make round holes or slots with uniform kerf width.

Figure 3 illustrates micrographs of a small hole pierced in a thin stainless steel shim 100 µm thick. The hole was pierced with a 7-15 nozzle and a proprietary auxiliary device to reduce the effective diameter of the AWJ exiting the mixing tube. Figure 3 are 3D micrographs of the top (entry side) and bottom (exit side) of the hole with a diameter smaller than 100 µm. As a rule of thump, the size of AWJ-cut features is slightly larger the beam diameter of the AWJ (or the diameter of the mixing tube). In other words, the smallest hole that can be pierced with the 7-15 nozzle with a mixing tube diameter of 380 µm is around 400 µm. The auxiliary device has effectively reduced the beam diameter of the AWJ factor of four or more. The advantage of using such a device is to enable relatively large AWJ nozzles and coarse abrasives to cut parts with features smaller than the diameter of the mixing tube. Note Figure 3 represents micrographs of the as-pierced hole without trepanning. The circularity of the hole would be significantly improved by trepanning after it is pierced.

Figure 4 illustrates three narrow slots machined in a stainless steel shim 0.25 mm thick. The kerf width of the slots was measured to be around 92 µm. These slots were machined with a 7-15 nozzle

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[5] http://www.omax.com/software.php

together with another auxiliary device to reduce the effective beam diameter of the nozzle. Note that the kerf width is smaller than that of a finger print left on the surface of the shim.

4.2 Components for green energy products

The versatility of waterjet technology has led to many potential industrial applications. For example, the ability to machine large-aspect-ratio slots and ribs on thin films by μAWJ technology could be taken advantage of for manufacturing components of microchannel plates used for fuel cells, reactors, reformers, and heat exchangers. Microchannel plates consisting of large-aspect-ratio slots and ribs, including both simple to complex patterns, were successfully machined cost effectively with AWJs on stainless steel and titanium shims. It was demonstrated certain slot/rib patterns are difficult and/or costly to be machined by conventional machine tools (Liu et al., 2008).

There are applications that components of devices made from certain materials with specific geometries are too expensive and too difficult or even impossible to fabricate with established machine tools. One of such examples regarding the fabrication of novel components of high-efficient small motors/generators is given below (Trimble, 2011). Depending on the parameters of the electro-magnetic circuit, some small electric motor/generator designs can benefit from surface wound armatures. In the simplest configuration, a surface wound armature consists of a set of conductors that carry current alternatively into or out of the planer cross section of the motor/generator (figure 5). According to Faraday's law, the voltage in the motor is directly proportional to the number of turns in the armature, and since larger voltages are often easier and safer to work with than larger currents, the conductor is often split into multiple wires or turns (figure 6). In the case where round wires are used to fill the conduction area, the wires do not fit the annular space and thus the compaction factor (or ratio of volume filled by conducting wires to total allotted conductor volume) is low. A lower compaction factor results in higher armature resistance and reduced performance. The compaction factor can be greatly improved by using conductors of a proportional shape (figure 7). One possible method to achieve this is to cut slits in copper tubing of the appropriate annular dimensions (figure 8).[6] The smaller the kerf width of the cuts, the better the compaction factor and the better the performance of the machine will be.

While designing a high-efficiency motor, researchers of the Precision Engineering Research Group (PERG) at MIT (http://pergatory.mit.edu/) ran into difficulty to machine large-aspect-ratio narrow slots on copper tubes shown in Figure 8. Due to the high reflectivity of copper, laser cutting splatters and is not an option. On the other hand, EDMs do not enable the wire to go through the tubes, and sinking EDMs are too slow and costly. Upon request from PERG, test cutting of the slots on copper tubes was conducted at OMAX using the 5-10 beta nozzle mounted on a Model 2626 JMC. Preliminary results have found to be successful, as illustrated in Figure 9. It appeared that μAWJ technology could be the only cost-effective tool capable of machining such slots with kerf width 300 μm and narrower on copper tubes. It is concluded that μAWJ technology has shown great promises to be an enabling technology for this method of surface armature manufacturing. OMAX will continue collaborating with the PERG at MIT to further develop and evaluate μAWJ technology for the intended application.

4.3 Biomedical components

Machining biomedical components for orthopedic implants and medical instruments is one of the primary market targets of the μAWJ technology. Professional market research has indicated that

[6] Patent pending

market conditions appear favorable for advanced micromachining technology due to the fact that medical devices are continually becoming smaller and more intricate in terms of size, shape, and material. Such a selection is based on several key factors in terms of the market trend and size, the urgent need for cost reduction for healthcare, and the optimum match of merits of waterjet technology and the nature of the biomedical components.

Miniplates and microplates for orthopedic implants to repair/reconstruct bone and skull fractures are one of the strong candidates to take full advantage of the merits of μAWJ technology. Experimental μAWJ nozzles were used to machined various patterns available from the literature (Haerle et al., 2009). Titanium is used most often for these plates because of its biocompatibility. While conventional machine tools have difficulty in machining titanium, AWJs cut titanium 34% faster than stainless steel at considerably low costs. The most benefit for using AWJs to cut these components is the fast turnaround because of the following features: (1) scalability, (2) setup simplicity, and (3) no tooling requirement. Therefore, a part from resizing from the master drawing to finish could be made in minutes to meet the need for emergency operations.

Figure 9 illustrates several samples of AWJ-machinied miniplates and microplates made of titanium and stainless steel. The mesh type of miniplates were made from titanium shim stock 0.34 mm thick. These plates are commonly used in facial and skull repair and reconstruction (Haerle et al., 2009). Machining was carried out at a nozzle pressure of 380 MPa with the use of the beta 5-10 nozzle and 320 mesh garnet at a flow rate of 0.05 kg/min. The fine-mesh miniplate (middle right photo) took about 20 minutes to complete.

Working with PERG at MIT (www.perg@mit.edu), we used the beta 5-10 nozzle to cut a flexure to be used as a component of a medical device (Nikolai, 2010). The material was 6061 T3 aluminum with a thickness of 9.5 mm. The key feature is the narrow bridges, with a target width of 0.25 mm, between two connecting members of the flexure. Figure 11 illustrates the photo of a portion of an AWJ-cut flexure. The two lengths, L1 and L2, shown in the figure are the widths of one of the narrow bridges and one of the connecting members of the flexure. Note that the width of the bridge was measured to be 0.31 mm, about 0.6 mm wider than the target value of 0.25 mm. The taper of the part was measured to be about 0.2 degree.

4.4 Planetary gear set

For meso-micro machining of mechanical components, the beta 5-10 nozzle was used to cut a set of planetary gear set to be refined for watch making, for instance. The set consists of seven gears including the sun gear (9.68 OD), the ring gear (19.05 mm OD), and five small planetary gears (3.55 mm OD). Figure 12a illustrates the drawings of the seven gears and how they are assembled. Figures 12b and 12c are the drawings for the gear mounting plate and the planetary gear carrier, respectively. These drawings are developed by using the pc-based CAD program – LAYOUT. Figure 12d illustrates the screen display of the LAYOUT for the actual arrangement of seven gears to be cut from a piece of a stainless steel sheet. In that figure, the tool paths of the gears, the traverse lines, and the lead-in and lead-out lines are color coded; they are displayed in the magenta, green, and orange colors, respectively. The start and stop points of the cutting are marked at the two ends of the traverse. Note that the tool paths are color coded to represent the edge quality. Tool paths with a magenta color is designated as an edge quality of 3 out of 5, with 5 as the best edge quality. The arrangement of the ring and sun gears is to save materials. It should be pointed out that the spaces between the individual planetary gears and between the planetary gears and the ring/sun gear can be minimized to save materials using nesting programs available commercially. For example, we could slightly increase the space between the ring and sun gears and fit the five planetary gears into that space to minimize the waste of raw materials. Part nesting is a critical consideration when parts are made from very expensive materials such as inconel, titanium, and other advanced alloys and composites.

The planetary gear was assembled using the parts cut with the beta 5-10 nozzle. Figures 12e and 12f show the front and back side of the assembled planetary gear. To demonstrate its functionality as a planetary gear, a 298:1 (71 rpm) micro spur gear head motor manufactured by Solarobotics (Model GM14a) was used to drive the sun gear that moves the other gears in rotary motion. Refinement of AWJ machining of micro gears will continue as the nozzles are being downsized. We anticipate that μAWJ technology would have considerable edge over existing micromachining tools for fabrication micro gears in terms of cost effectiveness, fast turnaround, material independence, and minimum to no heat affected zone.

4.5 Interlocking link

The 7-15 nozzle were set up together with the Rotary Axis to machine axisymmetric features. To demonstrate such a setup, a titanium tube with an OD and ID of 6.0 mm and 4.8 mm were mounted on the Rotary Axis. Interlocking features were machined on the titanium tube by the nozzle with the Rotary Axis rotating. A steel rod was inserted into the titanium tube serving as a sacrificial piece to protect the its opposite side from exposing to the AWJ. The steel rod also serves to prevent the tube from bending downward after the interlocking features were machined on the end of the titanium tube. Figure 13 illustrates a photograph of the interlocking link. Since there is not soldering joint on the tube, the link is quite strong as compared with similar ones that are welded together.

4.6 Multinozzle platform

Another advantage of downsizing the nozzle is that the water flow rate reduce accordingly. Depending on the size of the orifice, the number of nozzles that can be support by the pump increased according. For example, a 22.4 KW pump that is capable of supporting one 0.36 mm orifice operating at 380 MPa at a water flow rate of 3.4 l/min is capable of supporting four 0.18 mm nozzles operating at the same pressure. During Phase 1B, a multi-nozzle platform on which four 5-10 nozzles are mounted was designed, assembled, and tested, as illustrated in Figure 14. The platform was subsequently delivered for beta testing to one of our customers in the specialty jewelry manufacturing industry. With the four nozzles operating in tandem, four identical parts will be machined simultaneously to boost the plant productivity.

5. Summary and future work

5.1 Summary

Under the support of two NSF SBIR Phase I and II grants, OMAX Corporation has successfully demonstrated the feasibility for developing μAWJ systems capable of machining features around 100 to 50 μm. Prior to the award of the grants, several novel concepts have been conceived to take into consideration the change in characteristics from gravity-dominated flows to capillary-dominated microfluidics, the flowability and clumping tendency of very fine abrasives, and nozzle clogging of wet abrasives by backsplash water. Subsequently, patents pertinent to μAWJ machining were filed. A prototype of μAWJ system is under development under the support of the current SBIR Phase II grant.

During the course of the Phase I R&D, several research nozzles and auxiliary devices were developed, assembled, and tested for meso-micro machining. The nozzles and auxiliary devices with the incorporation of novel processes were first tested to demonstrate that the diameter of pierced holes and the kerf width of slots are all under 100 μm. The research nozzles were then used to machine miniature samples from different materials as a means to demonstrate the feasibility of developing μAWJ technology toward meso-micro machining. Samples include components for green energy production systems and medical implants and devices, a miniature planetary gear set, and a titanium interlocking link. The test results also demonstrated the versatility of waterjet technology in terms of material independence and technological and manufacturing merits unmatchable by most other machine tools. For enhancement of productivity, a multi-nozzle platform supporting up to four beta 5-10 nozzles was designed, assembled, and tested. This platform was subsequently delivered to one of our customers for beta testing.

5.2 Future work

There are multiple paths for commercialization of the μAWJ technology. First, for existing owners of OMAX's JMCS and/or MAXIEMs, They could readily operate multiple μAWJ nozzles to boost their productivity, provided that the ± 0.08 mm (Premier line) and/or 0.025 mm (XP line) position accuracy are adequate. For new customers who are interested in applying μAWJ technology for meso-micro machining, OMAX is in the process of developing new product lines of μJMCs specifically for those applications. We anticipate that the μJMC be a very cost effective precision meso-micro machining tool as the costly components of the precision XY traverse and the high-pressure pump will be downsized proportional to that of the μAWJ nozzles. For example, a 4 KW high-pressure pump is all that is required to drive a 5-10 or smaller nozzle. The optimum configuration of a μJMC would consist of a small footprint XY traverse and a low-power high-pressure pump. The downsized μJMC, with positioning accuracy better than our current JMCs, is expected to have considerable cost advantage over established tools such as lasers and EDM for meso-micro machining. As such, development of μAWJ technology will significantly improve the affordability of waterjet technology for meso-micro machining. Affordability will be the key factor for the commercialization and rapid and broad adoption of μAWJ technology worldwide.

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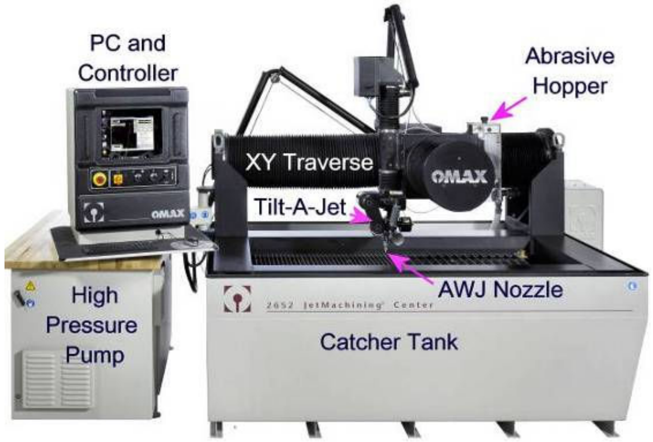
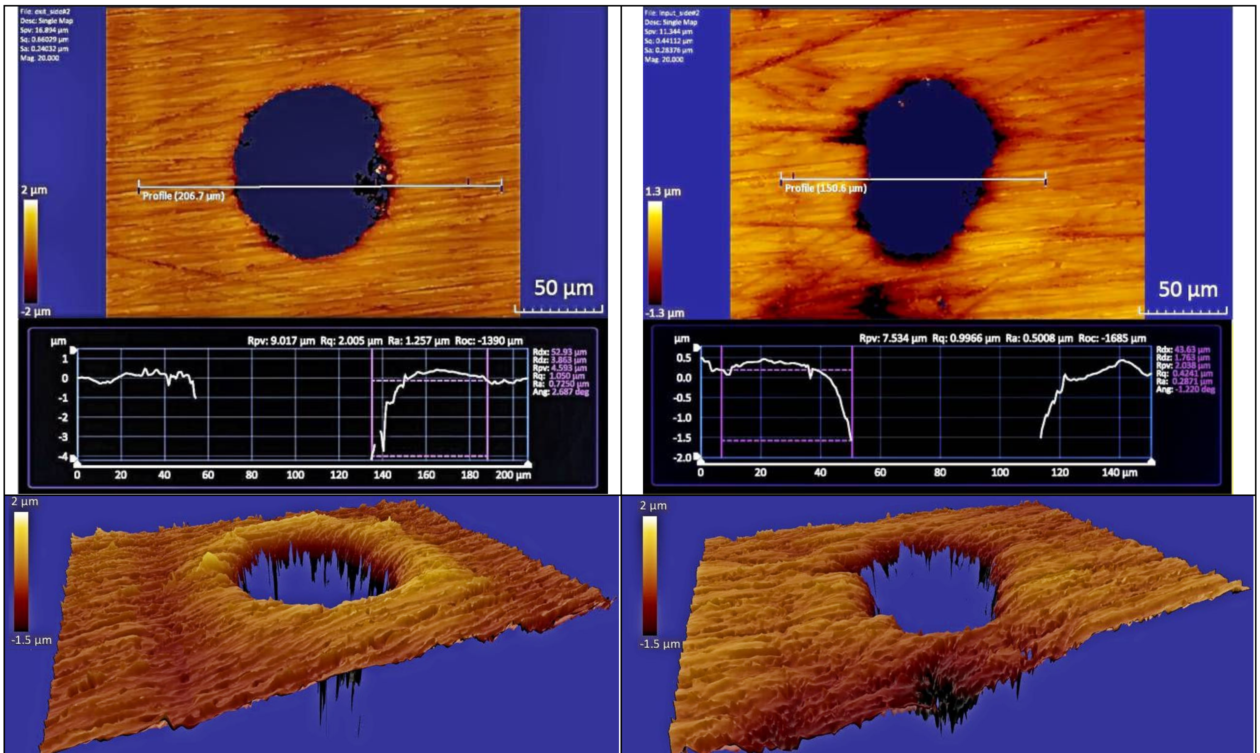


Figure 1. Model 2652 JetMachining Center

Figure 2. Compact 7-15 nozzle with a single feed tube and no appendage



a. Entry side	b. Exit side

Figure 3. Micrographs of the hole pierced on 316 stainless steel shim - courtesy of Zygo Corp and Microproducts Breakthrough Institute

a. Thee parallel slots	b. Micrograph of slot

Figure 4. AWJ-machined narrow slots using a novel auxiliary device (patent pending)

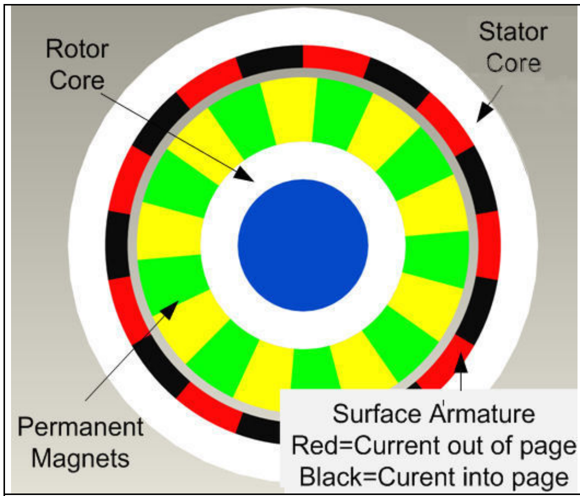


Figure 5. Typical configuration for a permanent magnet motor/generator

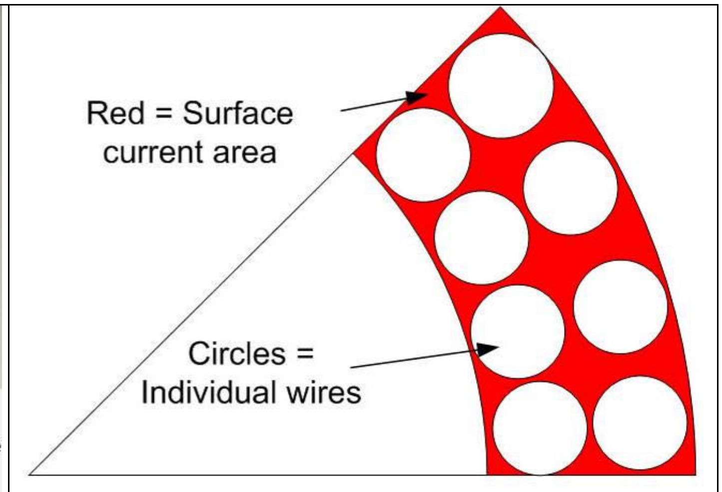


Figure 6. Schematic of multi-round-turn conductor

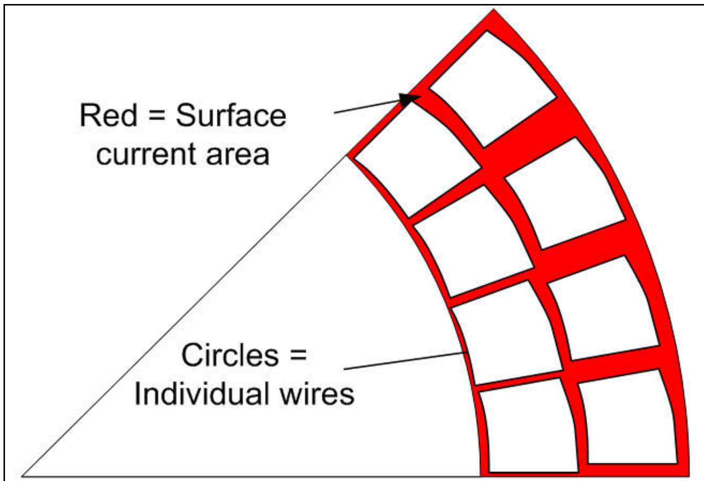


Figure 7. Schematic of multi-square-turn conductor

Figure 8. Solid model of cut tubing

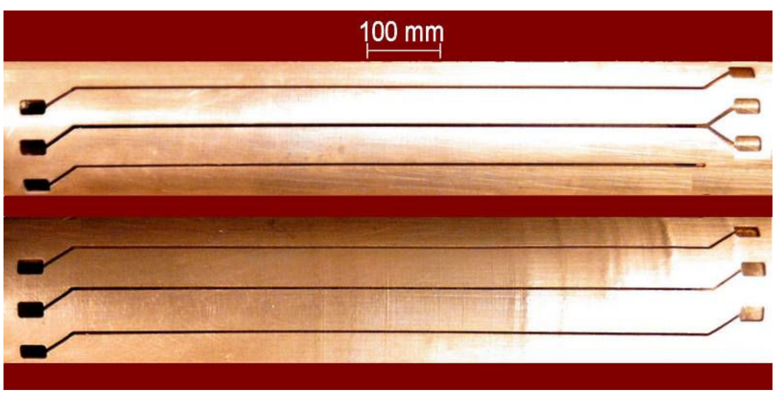


Figure 9. Sections of AWJ-slotted copper tubes (slot patterns provided by PERG at MIT (http://pergatory.mit.edu/)

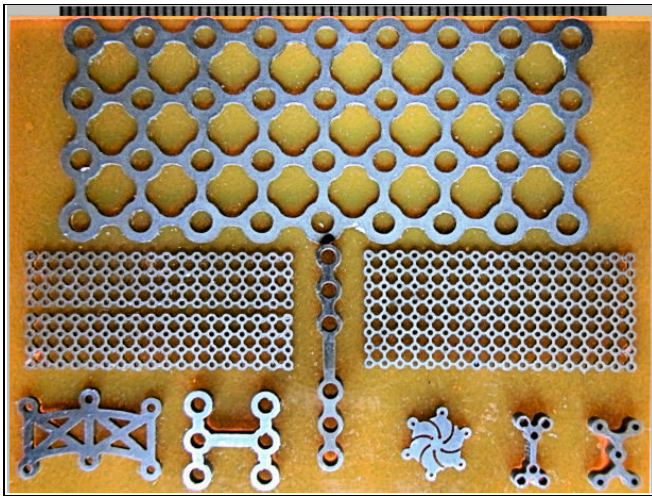


Figure 10. AWJ-machined orthopedic components – scale in mm

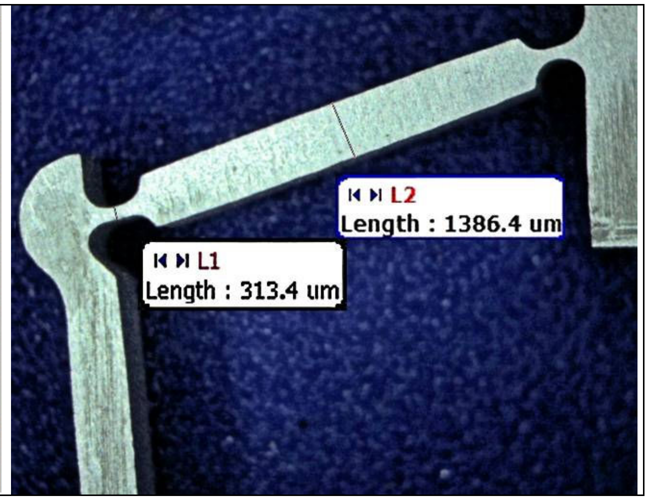
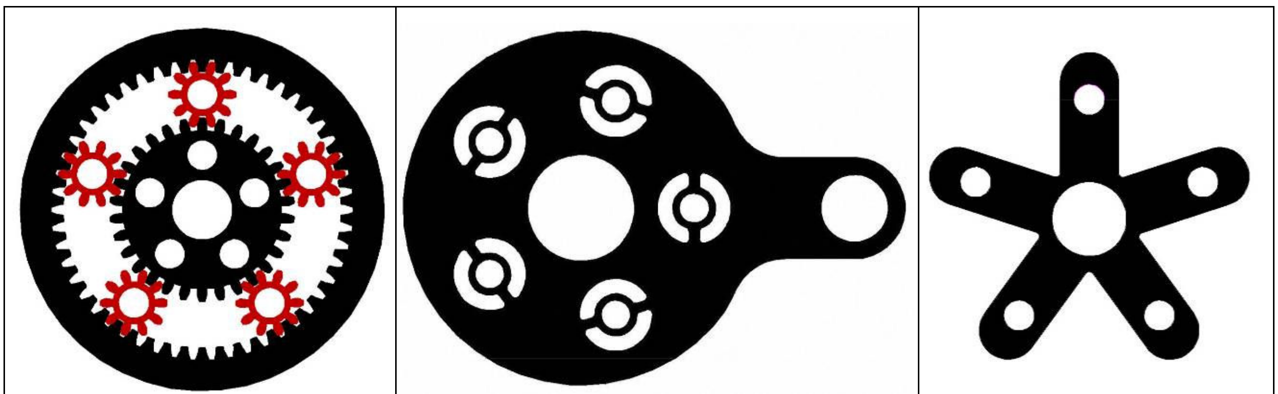
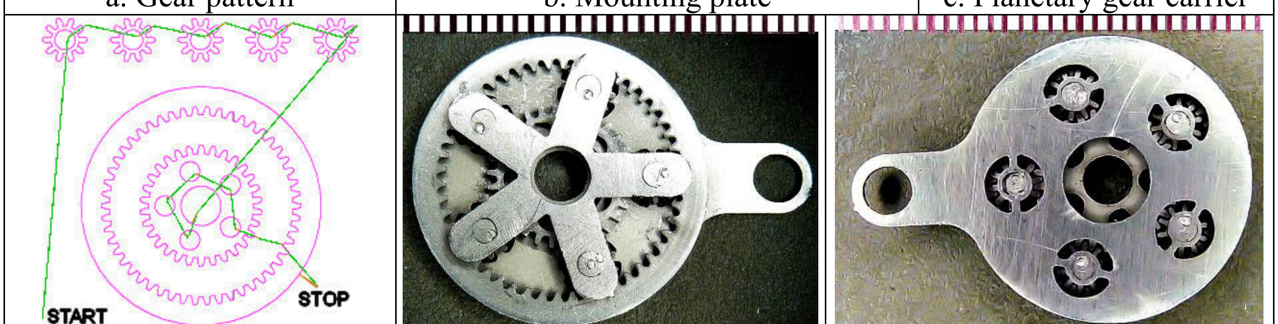


Figure 11. Mean features of a small flexure for a medical device (PERG at MIT)



a. Gear pattern | b. Mounting plate | c. Planetary gear carrier



d. LAYOUT display | e. Photo of planetary gear (front) | e. Photo of planetary gear (back)

Figure 12. AWJ-machined stainless steel planetary gear set – scale in mm

Figure 13. AWJ-machined interlocking link made from a solid titanium tube (0.64 mm OD)

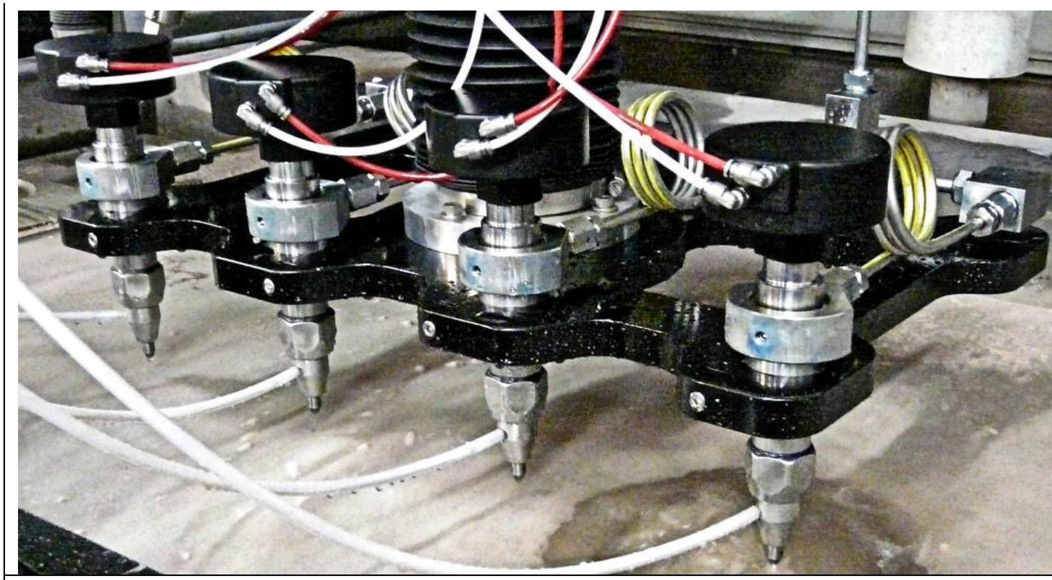


Figure 14. Multi-nozzle platform accommodating four beta 5-10 nozzles operating in tandem