American WJTA-IMCA Conference and Expo
November 2-4 ● New Orleans, Louisiana

Paper

NOVEL PROCESSES FOR IMPROVING PRECISION OF ABRASIVE WATERJET MACHINING

(Peter) H.-T. Liu[§]
OMAX Corporation
Kent, WA 98032
www.omax.com

ABSTRACT

Abrasive waterjet (AWJ) possesses several technological and manufacturing merits unmatched by most machine tools. As a "floppy" machine tool, AWJ has inherent characteristics that tend to cause certain blemishes in various degrees on the finished parts. For precision machining, such blemishes must be minimized. For example, blemishes include (1) edge taper as the result of the spread of the AWJ upon exiting the mixing tube; (2) damage induced by AWJ during the initial piercing of delicate materials including composites, laminates, and brittle materials such as glass and silicon wafers; and (3) the frosting and edge rounding on the jet entry surface and the chipping and burr on the jet exit surface. This paper is devoted to demonstrating several novel methods to minimize or mitigate the above blemishes to qualify AWJ as a precision machine tool.

Organized and Sponsored by WJTA® - IMCA®

[§] Senior Scientist

1. Introduction

Abrasive waterjet (AWJ) possesses several technological and manufacturing merits unmatched by most machine tools. As a “floppy” machine tool, however, AWJ inherently has a number of characteristics that could induce blemishes in various degrees on the finished parts. Such blemishes must be minimized in order for the AWJ to become a truly precision machine tool. For example, blemishes include (1) edge taper due to the spread of the AWJ after exiting the nozzle; (2) damage induced by AWJ during the initial piercing of delicate materials including composites, laminates, and brittle materials such as glass and silicon wafers; (3) the frosting and edge rounding on the jet entry surface and the burr and edge chipping on the cut edges of the jet exit surface. There are other blemishes that can be controlled by optimizing the process parameters. For example, a striation pattern is often formed on the AWJ-cut edge when the AWJ travels too fast. Slowing down the AWJ traverse speed reduces the amplitude of the striation pattern. Reducing the size of abrasives would also reduce the amplitude and wavelength of the striation pattern (Liu, 2014). Also, overcuts at the intersection between the lead-in and tool path result when the dwell time of piercing is too long. Controlling the dwell time during piercing is the key to mitigate overcutting.

Edge taper is the direct consequence of the spread of the AWJ after exiting the nozzle. Piercing damage takes place when the stagnating pressure building up inside the blind hole exceeds the tensile or adhesive strength of delicate materials (Liu, 2006a). Frosting and edge rounding result from the strayed particles outside the high-speed core of the AWJ (Liu, 2014). Burr and chipping on the exit edge are induced when the AWJ breaks through the bottom surface of the material, with chipping occurs mostly for brittle materials.

Extensive investigations have been conducted to understand the above characteristics. Several interim and permanent remedies have been developed to minimize the AWJ-induced blemishes. For example, an abrasive cryogenic jet (ACJ) using liquefied nitrogen as the working fluid was investigated to minimize the stagnation pressure inside the blind hole (Liu, 2006b). Based on the operational principle, a superheated AWJ or FAWJ was subsequently developed to emulate the ACJ (Liu et al., 2010). The success of the ACJ and FAWJ, however, has led to the development of two viable processes to mitigate piercing damage; Turbo Piercer and Mini Piercer are for cutting large and small internal features, respectively (patented). The Turbo Piercer manipulates the AWJ to reduce the stagnating pressure to be below the tensile strength of target delicate materials. The Mini Piercer applies low-pressure piercing together with vacuum assist.

In this paper, we will describe several processes and apparatus to minimize or mitigate the blemishes described above. Examples of the test parts cut with these processes and apparatus were presented to demonstrate their effects in improving the part accuracy.

2. Technical Objectives

Abrasive waterjet as a “floppy” machine tool has the tendency to introduce several undesirable features that degrade its performance for precision machining. The technical objectives of the R&D activities described in this paper are therefore to examine the performance characteristics of AWJ machining and develop novel remedies to mitigate those features. Our goal is to implement these remedies to quality AWJ as a precision machine tool for a wide range of materials and part sizes.

3. Technical Approach and Facilities

3.1 Technical Approach

AWJ is a versatile machine tool capable machining most materials from macro to micro scales. As a “floppy” machine tool, however, there are inherent behaviors of the AWJ process that could lead to certain blemishes on AWJ-machined parts. Such behaviors and the resulting blemishes include but are not limited to:

- AWJ spreading - edge taper
- Development of large stagnation pressure in blind holes – piercing damage in delicate materials
- Strayed abrasives – edge rounding and surface frosting
- Challenges in AWJ micromachining (feeding of fine abrasive in micro nozzle) – varying kerf width and skip cutting

Our approach was to conduct laboratory experiments to investigate in detail AWJ machining processes. Based on the understanding of these processes, novel remedies were developed to minimize or mitigate blemishes on AWJ-machined parts to achieve the goals described in Section 2.

3.2 Test facilities

3.2.1 MicroMAX® JetMachining® Centers and nozzles

OMAX has two product lines of equipment for AWJ precision machining, the OMAX JetMachining® Center and the MAXIEM JetMachining Center, to meet a wild range of machining needs. Under the current support of an NSF SBIR Phase II/IIB grant, OMAX has developed and commercialized micro abrasive waterjet (μAWJ) technology for precision meso-micro machining. One of the key objectives was to downsize the AWJ nozzle capable of machining features around 100 to 50 μm. Several micro nozzles together with novel accessories were developed to achieve the above objective. At present, in addition to our standard nozzles, there are three miniature nozzles at various developmental stages:

Nozzle	**Orifice ID in/mm**	**Mixing Tube ID in/mm**	**Optimum Garnet Size**	**Status**
7/15 Mini MAXJET5	0.007/0.18	0.015/0.38	≲ 150 mesh	In production
5/10 Mini MAXJET5	0.005/0.13	0.010/0.25	≲ 220 mesh	In beta testing
3/8 Nozzle	0.003/0.076	0.008/0.20	≲ 240 mesh	R&D

There were several challenges in downsizing the AWJ nozzle (5/10 and smaller).

- Difficulty in fabricating mixing tubes (ID < 0.010” or 0.25 mm) with good circularity and sufficiently large aspect ratio required for creating tightly collimated AWJ.
- It is important to size the abrasive such that its average size should be ≲ three times the mixing tube diameter to prevent nozzle clogging through bridging of two large abrasive particles. For very fine powdery abrasives, it is well known that they are difficult to feed consistently under the gravity feed mode.
- As the nozzle being further downsized, the 3-phase slurry flow through the mixing tube bore would transition from gravity-dominated to capillary-dominated microfluidic flow. According to the Hagen–Poiseuille equation, a 2-phase microfluidic flow resistance is proportional to the -

4 power of the diameter of the conduit. We anticipate that the 3-phase flow resistance of the microfluidic slurry flow through the mixing tube would also overcome the driving force, the high pressure, such that micro AWJ would no longer be effective for cutting.

Several novel processes, apparatus, and accessories, leading to five relevant patents, were developed to meet the above challenges. The µAWJ technology was subsequently commercialized by introducing a new product, the MicroMAX® JetMachining® Center**,** which debuted in September 2013 at the EMO (Hannover, Germany) and MD&D (Chicago) trade shows. Figure 1 is a photograph of the MicroMAX that was specially designed to more than match the requirements for precision meso-micro machining. With the addition of the MicroMAX, OMAX has extended the capability of AWJ machining from macro to micro scales. Refer to the link for a detail description of MicroMAX's specifications (https://www.omax.com/waterjet-cutting/machine/model/micromax).

3.2.2 Accessories

Accessories were developed to improve the performance of the µAWJ technology. They could be divided into several categories based on their functionalities. One of the accessories is a refocuser (patented – Liu and Shubert, 2014).

Refocusers and Stencil-Aided Waterjet System (SAWS)

These accessories were designed to further reduce the diameter for hole drilling and slot cutting. The refocuser is a short mixing tube, with ID smaller than that of the mixing tube, attached to the tip of the primary mixing tube. Only the core of the AWJ exiting the primary mixing tube would be allowed to enter into the blind hole and the abrasives outside of the core will be discarded. As such, the hole drilled with the refocuser would be considerably smaller than that drilled without the refocuser.

A second accessory under this category is Stencil-Aided Waterjet System (SAWS). The SAWS is formed by two pieces of carbide plates with the provision of a narrow slit along the edges where the two carbide plates meet. With the AWJ traversing along the axis of the narrow slit, the kerf widths of the slots cut with the SAWS setup would be limited by the width of the sacrificial slit.

Vacuum Assist Kit

The vacuum assist kit was developed for low-pressure piercing when the vacuum created by the Venturi effect was too low to entrain all the abrasive fed from the hopper. The additional vacuum issued by the vacuum assist kit would help remove the excessive abrasives through the vacuum discharging line into a waste tank. As soon as high-pressure cutting resumes, the abrasives are fully entrained by the vacuum generated by the full-power AWJ. The above operation is carried out automatically with software control of the on-off valves.

Tilt-A-Jet

The AWJ is a "floppy" machine tool. The diameter of the AWJ spreads and meanders after it exits the nozzle. Therefore, there is a natural taper on the edge of the AWJ-cut parts. The Tilt-A-Jet (TAJ) was designed to remove taper from the AWJ-cut part through dynamically tilting during cutting (https://www.omax.com/waterjet-cutting-accessories/tilt-a-jet/61). The TAJ was also adapted for the MicroMAX.

3.3 CAD/CAM programs

OMAX's PC-based CAD program, LAYOUT, was designed to either draw from scratch or import from AUTOCAD or other CAD software tool paths of parts for AWJ machining. The tool paths were subsequently passed onto the CAM program, MAKE, where various parameters pertaining to the workpiece (material types and thickness), the abrasive waterjet (pressure and nozzles), the abrasives (type, mesh, and mass flow rate), and cut qualities (from Q1 through Q5) were specified. The part according to the tool paths was cut automatically by MAKE, which controls operations of a suite of hardware accessories such as the TAJ for taper compensation, Rotary Axis and A-Jet for 2D and 3D machining.

4. Results

4.1 Mitigating edge taper

In the absence of the TAJ, the edge cut with the AWJ exhibits a taper due to the spreading of the AWJ as it travels downstream. The TAJ tilts dynamically to compensate for the edge taper. Before cutting a part that requires a minimum taper, a taper compensation test was first conducted by cutting a series of coupons with the same thickness the part to be cut. A taper compensation program was used to dial in the tool and taper offsets to achieve the minimum edge taper.

As an example to demonstrate a part that requires a minimum taper, Figure 2 illustrates an interlocking part made of 0.125" thick titanium. It consists of an inner and outer components that fit snuggly with a very narrow gap, say around 20 μm. The part was cut on the MicroMAX with a 5/10 beta nozzle using 240 mesh garnet at a flow rate of 0.11 lb/min (50 gram/min). In the presence of an edge taper, the two components could only be locked into position from one direction by flipping one of them. As a result, one component has a positive taper angle and the other a negative taper angle.

By activating the TAJ, the part was cut nearly taperless. The two components could then be locked into position from both directions. The part has adequate precision such that the two components could be locked into position by rotating one of the components any multiples of 12 degrees (i.e., there are a total of 30 teeth).

4.2 Gear Making

AWJ is an excellent gear maker. OMAX LAYOUT has a gear generation package which is a subset of the "Parametric Shapes Tool". The gear generator supports internal and external gears, racks, sprockets, in both U.S. and metric standards, as illustrated in Figure 3. Resulting geometry can then be further edited using LAYOUT tools to combine with other shapes. Gear cutting could by executed (1) without using the TAJ but flipping gears to partly cancel taper or (2) with the use of TAJ to make them taper free. For an in-depth discussion of AWJ gear making and examples, refer to Olsen (2015).

In the early developmental stage of the μAWJ technology, a planetary gear set consisting of five planetary gears was fabricated, assembled, and operating driven by a micro motor operating with two AAA batteries (Liu and Schubert, 2012). The gear set was cut with a 5/10 nozzle and 320 mesh garnet at 0.1 lb/min (45 gram/min). No TAJ was used and the gear components were flipped to match the taper.

Most recently, in demonstrating the performance of the MicroMAX®, in terms of its cutting precision and vibration isolation capability three sets of cycloidal gears with different sizes were cut from 2.9 mm thick titanium using the 5/10 nozzle and 240 mesh garnet at 0.11 lb/min (0.5

gram/min). Cycloidal gears are traditionally designed for making watches and clocks. Figure 3 illustrates the photographs of the three sets of cycloidal gears. The large gears were cut according to the tooth paths. Smaller gears were cut by nesting several of them together. A narrow tab was designed into one of the tips of each gear to keep it from falling into the catcher tank. Individual gears were then extracted by machining away the tabs. The three sets of gears were mounted on pins that were fixed on supporting titanium plates. Each set of gears could be rotated by hand with ease.

4.3 Delicate Materials

Delicate materials include composites, laminates, and brittle materials such as glass and silicon wafer are difficult to machine by conventional AWJ processes. During the initial piercing of these materials, a large stagnating pressure is developed, as the high-speed waterjet decelerates, stops, and reverses near the bottom of the blind hole, before breakthrough takes place. These materials would result in delamination or internal cracking provided the stagnating pressure exceeds their tensile/adhesive strengths (Liu, et al., 1998). In other words, conventional AWJ is simply is incapable of preserving the structural integrity of parent materials. Considerable efforts were made to understand the AWJ piercing process and several interim remedies were developed to mitigate AWJ piercing damage. One of the remedies used an abrasive cryogenic jet (ACJ) with liquefied nitrogen as the working fluid (Liu, 2007). The liquefied nitrogen remains a liquid under pressure but begins to evaporate as soon as it exits the mixing tube. Therefore only abrasive goes into the blind hole without developing stagnant pressure and therefore no piercing damage results.

Another remedy was a super-heated AWJ or FAWJ to emulate the ACJ. The water was superheated to beyond the boiling temperature. It evaporates as soon as the waterjet exits the mixing tube and only abrasives enter into the blind hole without inducing stagnating pressure and piercing damage. The FAWJ was used to machine a variety of delicate materials to demonstrate the success in mitigating piercing damage (Liu et al., 2010).

In practice, both the ACJ and FAWJ are not suitable for operating in industrial environments because of their complexity and severe operating temperatures. The experiences gained in these two investigations, however, have helped understand the AWJ piercing process leading to piercing damage of delicate materials. Based on such understanding, two proprietary processes for mitigating piercing damage in delicate materials were developed. These processes utilize air-assisted abrasive feeding (Turbo Piercer) and low-pressure piercing with vacuum assist (Mini Piercer), respectively. The vacuum assist helps to remove excess abrasives accumulated in the mixing chamber at low-pressure piercing where the Venturi vacuum is too weak to entrain and accelerate all the abrasives fed from the hopper. Otherwise, nozzle is prone to be clogged by excessive abrasives left in the mixing chamber/mixing tube. Since the air-assisted feeding process, Turbo Piercer, tends to increase the spread of the AWJ, it is most suitable for machining relatively large features. On the other hand, low-pressure piercing with vacuum assist with the Mini Piercer does not affect the geometry of the AWJ and is suitable for machining small features especially when miniature nozzles are used.

Figure 4 illustrates photographs of an aluminum-laminate sample (BAC1534-63F) pierced with the Turbo Piercer. The laminate consisted of 19 aluminum sheets 0.076 mm thick with an overall thickness of 1.6 mm. The 14/42 nozzle with 80 mesh garnet were used. Piercing was carried out by slightly pressurizing the abrasive hopper. Cutting was performed at $p = 380$ MPa. The photographs on the left and right correspond to the samples machined before and after Turbo Piercer was optimized, respectively. The effectiveness in mitigating delamination of the optimize Turbo Piercer is evident. Figure 5 illustrates photographs of internal patterns machined with Mini Piercer on the aluminum laminate and a fiber-reinforced plastic (0.85 mm thick), respectively. The 7/15 nozzle with the 240 mesh garnet at 0.68 gram/min was used to cut these parts. Piercing and cutting were carried out at p = 41 MPa and 380 MPa, respectively. No delamination is present on any of the four identical patterns machined on each of the finished part.

One of the premier composite materials is PEEK (polyetheretherketone). It has among the best chemical resistance of any thermoplastic material and is capable of maintaining stiffness at elevated temperatures. As a result, it is has been often specified for high temperature applications in aerospace, semiconductor, medical, and food processing. PEEK has found to be superior to titanium for manufacturing implants as PEEK is not only biocompatible but also much more bone-friendly and is much more compatible with diagnostic imaging than metal implants. Sample materials of unfilled and carbon fiber reinforced PEEK were furnished by Victrex to conduct test cutting with AWJ. The planetary gear set described in Section 4.2 was cut using both PEEK materials. Figure 6 illustrates two sets of nested components and assemblies of two planetary gear sets made from the two materials. The components were machined without the TAJ activated. The assemblies were as cut without any secondary processes except the planetary gears were flipped to account for the edge taper. For the carbon reinforced PEEK, the carbon fibers were cut cleanly without fray. The embedded carbon fibers could present difficulties to cut with other machine tools.

The Mini Piercer with a 5/10 nozzle was used to cut small internal features on the aluminum laminate described above. In this case, pressures of 41 MPa and lower were required to mitigate delamination. For such low pressures, the Bernoulli vacuum developed after the waterjet exits the orifice is too weak to entrain all the abrasives fed from the hopper. Vacuum assist is required to remove excessive abrasives accumulated in the mixing chamber. Otherwise, the mixing tube will be clogged by the excessive abrasives. As soon as piercing is through, normal high-pressure cutting at 380 MPa resumes to cut internal features. Figure 7 illustrates the top and bottom surfaces of the aluminum laminate.

For thin workpieces such as the 0.076 mm individual shims of the aluminum laminate, the best way to machine them with AWJ was through stack cutting. It is imperative that individual shims must be firmly adhered to one another to resist delamination during piercing and easily separated after cutting is complete. The top and bottom shims of the stack would serve as the sacrificial covers to protect the interior ones from frosting (top shim) and burr (bottom shim). After the stack is cut, the internal shims would be nearly identical with no frosting and burr, as illustrated in Figure 8.

4.4 AWJ Meso-Micro Machining

The MicroMAX was built to meet the requirements for precision meso-micro machining. With the use of the 5/10 nozzle and abrasives 240 mesh and finer, small parts with miniature features could be machined with high precision. For example, the smallest cycloidal gear set shown in Figure 3 could only be cut with nozzles 5/10 or smaller. Certain features such as the minimum diameter of holes and minimum kerf width of slots are determined by the diameter of AWJ. As a cold cutting process with no heat induced distortion and minimum force exerted onto the workpiece, AWJ is capable of cutting very thin webs if the AWJ is steady and minimum nozzle vibration. Proprietary processes, apparatus, and hardware components were incorporated into the design of the MicroMAX to achieve constant feed rate of fine abrasives and minimum nozzle vibration. Another criterion is that the target material must be sufficiently stiff to support the thin webs.

The beta 5/10 nozzle mounted on the precision MicroMAX equipped with the TAJ and vibration isolation is fully capable of machining micro-size features. An important example is the machining of nearly taperless thin webs used as a critical component - flexures – of mechanical load cells (Section 4.5). A test part consisting of five thin webs with widths of 0.5, 0.25, 0.1, 0.076, and 0.05 mm were machined to demonstrate the above capability. The 5/10 nozzle was operating at 413 MPa. The abrasives was 240-mesh garnet with a mass flow rate of 50 gram/min. Titanium with a thickness of 2.9 mm was chosen as the target material to take advantage of its large ratio of stiffness versus weight. Prior to machining the parts, the TAJ was dialed in to achieve a taper angle of less than 0.126 degree. Figure 9 illustrates the top and bottom surfaces of one of the test parts. Note that the webs appear to be thinner on the jet entry surface than on the jet exit surface because the induced frosting and edge rounding on the entry surface. The web with the width of 0.05 mm tended to be slightly warped most likely due to stress release or insufficient material stiffness. Note that the length-to-width and length-to-thickness ratios of the 0.05 mm wide web are 125 and 2.54, respectively. Titanium parts with such large aspect ratios would be difficult to cut with other machine tools. For example, the heat generated by CO_2 laser could lead to considerable warping/twisting or even breakage of the thin webs; a large amount of slag or recast could left behind as the molten metal runs down the web walls solidifies (Liu, 2015). It should be pointed out that, by reducing the aspect ratio or for materials with high stiffness in the annealed state, thin webs with widths less than 0.05 mm could be machined with the 5/10 nozzle on the MicroMAX. As a versatile tools, such micro-size webs could be machined from a wide range of materials, which is beyond the capability of most machine tools.

4.5 Case Studies

The first academic and industrial installations of the MicroMAX are at the Hobby Shop of MIT. Two case studies were presented in this section to demonstrate the real-world applications of the MicroMAX. One of the studies was a reengineering of a Rostock MAX 3D printer at MIT's Hobby Shop. The original printer had injection-molded linkages and laser-cut plastic frame, which proved to be unstable and brittle in some places. These linkages and plastic frame were subsequently replaced with aluminum counterparts cut with AWJ using the MicroMAX (Figure 10). The reengineered printer results in a lighter, stiffer, and more heat-resistant structure.

The second case study applied the MicroMAX equipped with the TAJ for machining nonlinear stiffening load cells (Kluger et al., 2015). These load cells, with high resolution (within 1% of the force value) that can function over a large force range (5 orders of magnitude), and with minimal hysteresis and intrinsic geometric protection from force overload, was developed (patent pending). The stiffening nature of the load cell causes its deflection and strain to be very sensitive to small forces and less sensitive to large forces. High stiffness at high forces prevents the load cell from over-straining. The detailed design and theory of the load cell was given elsewhere (Kluger et al., 2015). AWJ was chosen as the machine tool to manufacture the symmetric and monolithic load cell consisting of four 1 mm thick springs as the force sensing elements. The nonlinear springs with cantilever beams that increasingly contact rigid surfaces with carefully chosen curvatures as more force is applied was physically implemented. A 7/15 nozzle operating at 380 MPa and using 240 mesh garnet at 0.68 gram/min was use to cut the load cell. Figure 11 is the AWJ-machined load cell and the inserts used for an optional setup. Figure 12 illustrates the experimental setups for two configurations, one without, and the other with the inserts in place (Figure 12a and 12b). Figure 12c presents the test results for the two configurations. The nonlinearity of the response to small and large load is evident.

5. Summary and future work

5.1 Summary

Abrasive waterjet (AWJ) has several technological and manufacturing merits that cannot be matched by most other machine tools. However, as a “floppy” machine tool, AWJ presents several challenges for precision machining. OMAX has overcome most of the challenges in order to elevate the AWJ as a versatile precision machine tool. This paper examines several undesirable characteristic of AWJ and the resulting blemishes left on AWJ-cut parts. The blemishes include (1) edge taper, (2) AWJ piercing damage in delicate materials, (3) frosting and edge rounding on the entry surface and chipping and burr on the exit edge, and (4) challenges in downsizing of AWJ nozzle for micromachining.

The accessory Tilt-A-Jet (TAJ) that is capable of tilting on the fly the nozzle head +/- 9 degrees from the vertical was used to demonstrate nearly taper free AWJ machining. The TAJ tilts dynamically during cutting such that the part is nearly taper free while the scrap has twice the taper. An interlocking part that could be locked into position from both directions was machined to demonstrate the performance of the TAJ.

Two proprietary processes, Turbo Piercer and Mini Piercer, were developed for mitigating piercing damage of delicate materials. Turbo Piercer and Mini Piercer were most suitable for machining large and small internal features, respectively. Internal features on aluminum laminates, fiber reinforced plastics, PEEK were machined to demonstrate the ability of mitigating piercing damage using the two Piercers.

AWJ stack machining was applied to cut internal features on thin aluminum shims. Not only is stack machining an effective means to stiffen the thin shims but also significantly increases the productivity. The top and bottom shims serve as the sacrificial covers while the internal shims are free of frosting, edge rounding, edge chipping, and burr.

As the AWJ continues downsizing toward micromachining, the size of the abrasives must decrease to avoid nozzle clogging by large abrasives. It is well known that powdery fine abrasives 320 mesh and finer tend to clump together and forms worm holes and are difficult to feed under gravity. Inconsistent abrasive feeding would vary kerf widths and cause skip cutting (Liu, 2014). Proprietary processes and apparatus were developed to mitigate clumping and the formation of worm holes and therefore achieve constant abrasive feed rate. As a result, we are able to feed abrasives as fine as 350 mesh for meso-micro machining (Liu, 2014).

In addition, the excellent gear making capability of AWJ was demonstrated by cutting cycloidal and planetary gears made from titanium and PEEK composite, unfilled and carbon fiber reinforced. The cycloidal gears are often used in watch making.

Titanium test parts with webs as narrow as 0.05 mm were machined on the MicroMAX using the beta 5/10 nozzle with the TAJ activated. Such a combination ensures that all the webs were cut precisely. These are attributed to several technological merits of the AWJ in terms of cold cutting and minimum impact force on the workpiece. The incorporation of the vibration isolation mechanism ensures that nozzle vibration is minimized. The slight distortion of the 0.05 mm wide web shown in Figure 9 is likely caused either by stress relief or by inadequate material stiffness. Webs with widths < 0.05 mm could be machined with the same setup either by reducing the aspect ratio or by selecting materials of high stiffness.

Two case studies were presented by using the MicroMAX for real-work applications. The first study was performed at MIT by replacing injection molded linkages and laser-cut frame with AWJ-cut aluminum counterpart. The second case study applied the MicroMAX for machining a monolithic, stiffening nonlinear load cell capable of high resolution with a wide force range (Kluger et al., 2015).

5.2 Future Work

The result of commercialization of the μAWJ technology has led to the award of an NSF SBIR Phase IIB Supplemental funding for continuing refinement of the MicroMAX for meso-micro machining. One of the tasks was to continue downsizing the AWJ nozzle toward micromachining. Preliminary results showed that a 3/8 combination was successfully operating to cut miniature parts. Figure 13 illustrates the progress toward AWJ micromachining by showing photographs of several tweezers machined with nozzles of different sizes. Other tasks involved the upgrade of the MicroMAX for 3D machining and the improvement of ergonomics.

Acknowledgments

This work was partly supported by an OMAX IR&D fund and by an NSF SBIR Phase II/IIB Grant #1058278. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. The author wishes to thank OMAX's technical staff members for their teamwork. They are responsible not only for the design and production release of the MicroMAX but also for the development and upgrade of a rich set of accessories which enhance the performance of the MicroMAX for precision meso-micro machining.

References

Liu, (Peter) H.-T. (2015) "Abrasive-waterjet machining of most materials from macro to micro scales," Proc 2015 TechConnect World Innovation Conference and Expo, June 14-17, Washington DC.

Liu, (Peter) H.-T. (2014) "Roles of Abrasives in AWJ Meso-Micro Machining," Proc 22nd International Conference on Water Jetting, the Netherlands, 3 – 5 September.

Liu, H.-T. (2006a) "Collateral Damage by Stagnation Pressure Buildup during Abrasive-Fluidjet Piercing," Proc. 18th Int. Conf. On Water Jetting, Gdansk, Poland, September 13-15.

Liu, H.-T. (2006b) "Hole Drilling with Abrasive Fluidjets," Int. J. of Adv. Manuf. Tech., Vol. 32, pp. 942-957. (DOI 10.1007/s00170-005-0398-x).

Liu, (Peter) H.-T. (2014) "Roles of Abrasives in AWJ Meso-Micro Machining," Proc 22nd International Conference on Water Jetting, the Netherlands, 3 – 5 September.

Liu, H.-T. and Schubert, E. (2012) "Micro Abrasive-Waterjet Technology (Chapter Title)", Micromachining Techniques for Fabrication of Micro and Nano Structures, Ed. Mojtaba Kahrizi, INTECH Open Access Publisher, ISBN 978-953-307-906-6, January, pp. 205-34

Liu, H.-T., Schubert, E., McNiel, D., and Soo K. (2010) "Applications of Abrasive-Waterjets for Precision Machining of Composites," Proc. SAMPE 2010 Conference and Exhibition, May 17-20, Seattle, WA.

Liu, H.-T., Miles, P., and Veenhuizen, S. D. (1998) "CFD and Physical Modeling of UHP AWJ Drilling" Proc. 14th Int. Conf. on Jetting Technology, Brugge, Belgium, September 21 – 23, pp. 15-24.

Kluger, J. M., Sapsis, T. P., and Slocum, A. H. (2005) "A High-Resolution and Large Force-Range Load Cell by Means of Nonlinear Cantilever Beams," Precision Engineering, http://dx.doi.org/10.1016/j.precisioneng.2015.08.003.

Olsen, C. (2015) “Manufacturing Gears with Water Machining,” Feature Article in Gear Production, March.

Figure 1. MicroMAX JetMachining Center

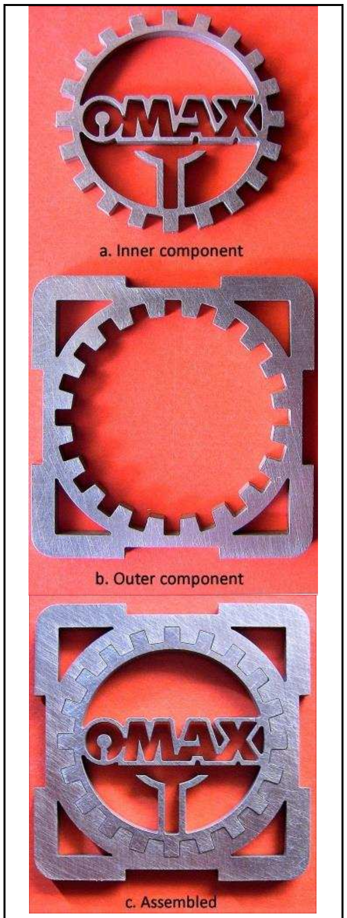


Figure 2. 2.9 mm thick well-matched interlocking part

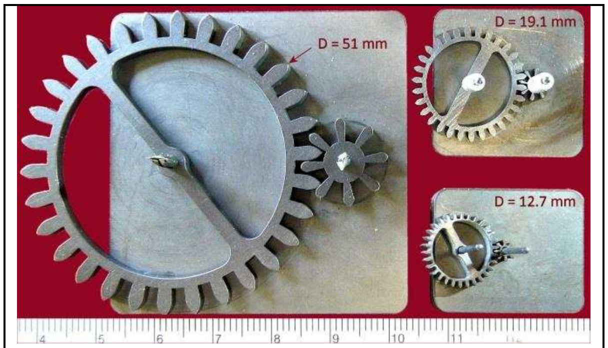


Figure 3. Cycloidal gear sets made from 2 mm thick titanium

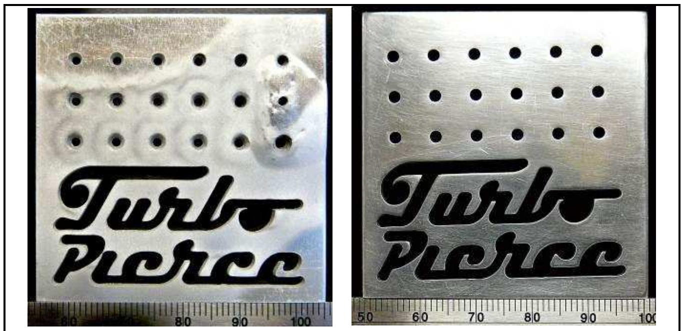

a. Before optimized b. After optimized

Figure 4. AWJ-machined internal features on aircraft aluminum laminate with Turbo Piercer

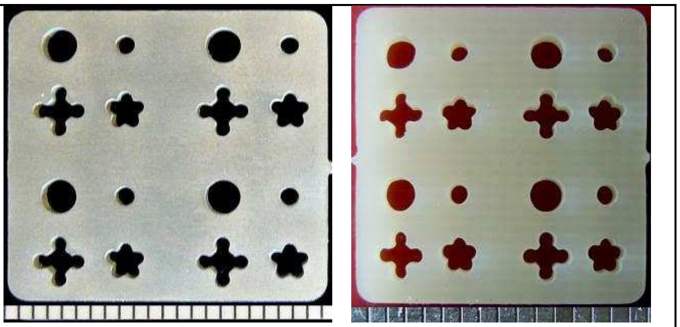
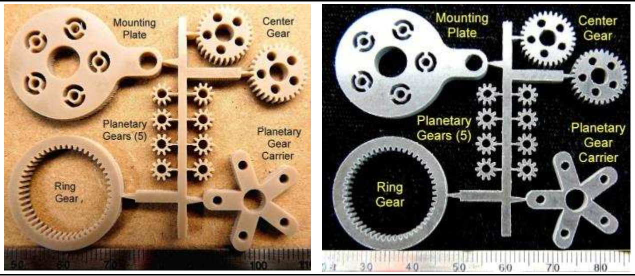
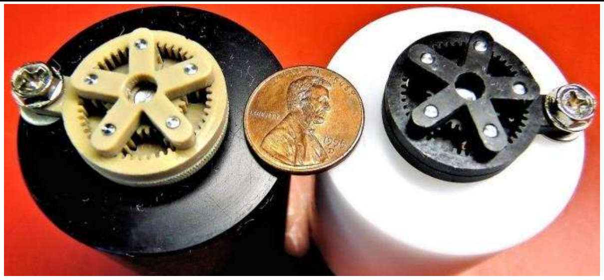

a. Aluminum laminate b. Fiber-reinforced plastic

Figure 5. AWJ-machined internal patterns on delicate materials with Mini Piercer (Scale: mm)



a. Unfilled b. Carbon fiber reinforced



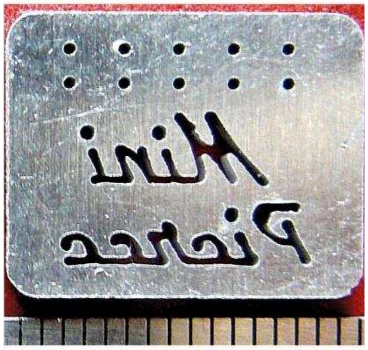
c. Assembled planetary gear sets

Figure 6. Planetary gear sets made from PEEK

Aluminum Laminate

(19 layers of 0.076 mm thick shims)

a. Top view



b. Bottom view

Figure 7. Internal features cut with the Mini piercer on aluminum laminate

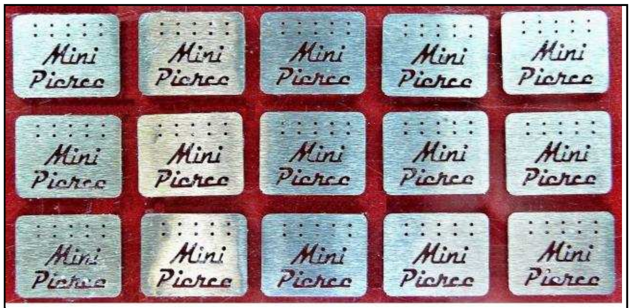
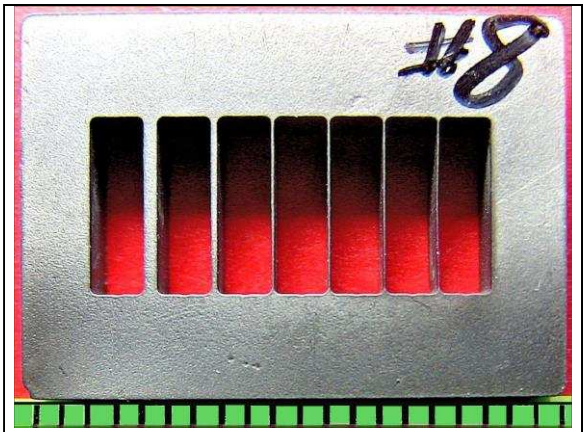
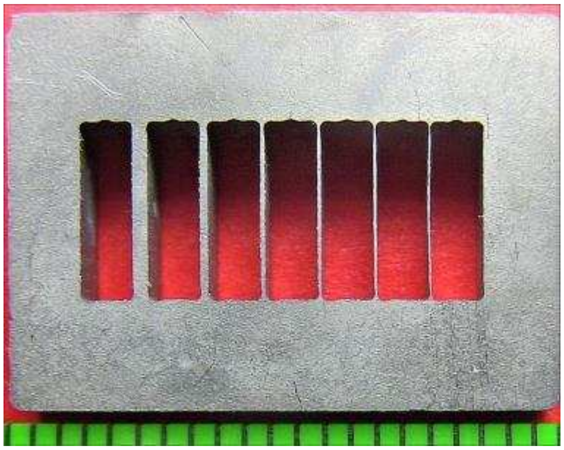


Figure 8. Interior 76 mm thick aluminum shims of AWJ-machined stack

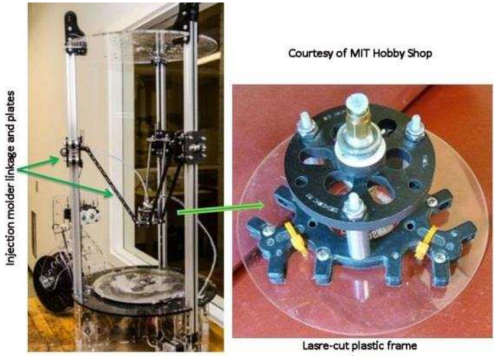


a. Top view



b. Bottom view

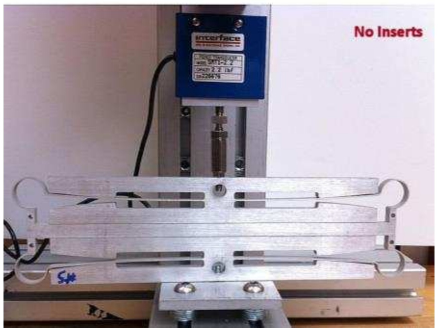
Figure 9. Test parts with thin webs



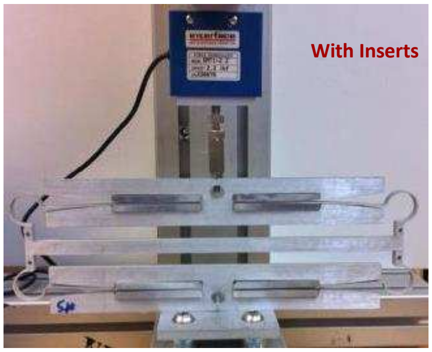
a. Before

b. After

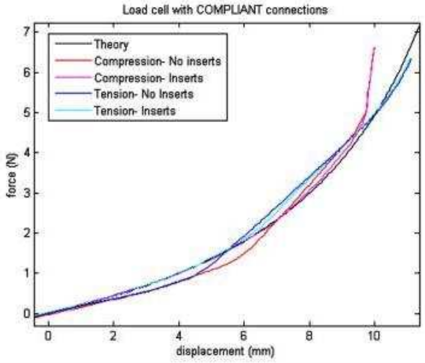
Figure 10. Reengineering of Rostock MAX 3D printer



a. Setup #1



b. Setup #2



c. Test results

Figure 12. Setups of load cells and results of force measurements (Kluger et al., 2015)

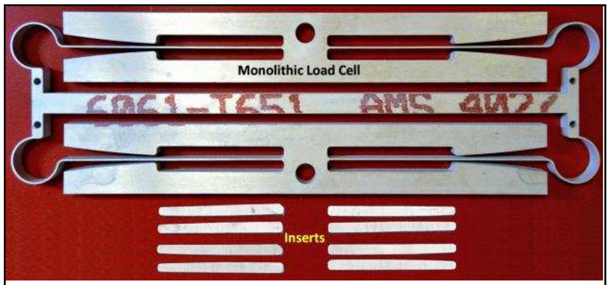


Figure 11. AWJ-cut nonlinear and monolithic load cell on the MicroMAX

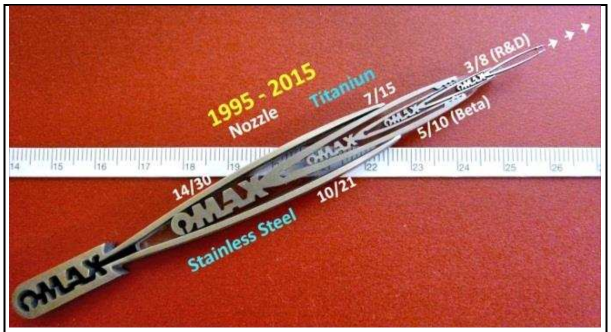


Figure 13. Progress in AWJ micromachining