International Journal of Emerging Engineering Research and Technology
Volume 7, Issue 6, 2019, PP 31-46
ISSN 2349-4395 (Print) & ISSN 2349-4409 (Online)

Performance Comparison on Meso-Micro Machining of Waterjet, Lasers, EDM, and CNC Milling

(Peter) H.-T. Liu*

Sr. Scientist, OMAX Corporation, 21409 72nd Ave. S. Kent, WA 98032, USA.

***Corresponding Author:** (Peter) H.-T. Liu., Sr. Scientist, OMAX Corporation, 21409 72nd Ave. S. Kent, WA 98032, USA, Email: Peter.Liu@omax.com*

ABSTRACT

The success in developing and commercializing micro abrasive-waterjet (μAWJ) technology has elevated waterjet as one of the meso-micro machining tools. It often competes on equal footing with lasers, electric discharge machining (EDM), and other micro machining tools. Waterjet possesses several technological and manufacturing merits unmatchable by other tools. Cutting tests were conducted using waterjet, lasers, wire EDM, and CNC milling to cut several parts with delicate features of meso-micro scales. The performances of these tools were qualitatively and quantitatively evaluated by inspecting photographs and micrographs of miniature parts and comparing them with the corresponding tool paths. Several μAWJ nozzles capable of achieving kerf widths as fine as 250 μm were used in the cutting tests. Test results show that waterjet is superior to the other tools in terms of the versatility, preservation of properties of parent materials, fast cutting speed, and cost effectiveness. For example, waterjet cuts at least one order of magnitude faster than lasers and wire EDM. Heat generated by these thermal-based tools induced a heat affected zone (HAZ) on the part edges, leading to damage such as discoloring, warping, and the presence of excessive slag. Remedies are available to minimize the heat damage by pulsing the laser at high frequencies and cutting with wire EDM via multiple passes, resulting in considerable slowdown in the cutting speed. As far as the cutting accuracy for thin materials is concerned, the solid-state laser performs the best, followed by the wire EDM, the 5/10 nozzle, the CO_2 laser, and the 7/15 nozzle.

Keywords: *Micro-Abrasive Waterjet, Heat Affected Zone, Meso-Micro Machining, Material Independence, Flexure, Micrograph, Tool Path, Load Cell*

INTRODUCTION

Under the support of an NSF SBIR Phase II/IIB grant, OMAX developed and commercialized micro-abrasive waterjet (μAWJ) technology, culminating in a new product MicroMAX® Jet Machining® Center (JMC) for meso-micro machining.[1] With the addition of the MicroMAX, waterjet has established the full capability of multi-mode machining of most materials from macro to micro scales for a wide range of part size and thickness (i.e., the "7M" advantage – [1]. Waterjet possesses several technological and manufacturing merits that are unmatched by most machine tools:

- A "green" machining process that uses no toxic machining fluid and produces no hazardous waste
- Material independence – cuts virtually any material from metal to nonmetal, and anything in between including nanomaterials with large gradient of nonlinear material properties [2]
- Cold cutting with low force exerted on work piece [3]
  - Cuts at high speeds without inducing a heat affected zone (HAZ)
  - Preserves structural and chemical integrity of parent materials
  - Machines large-aspect-ratio thin webs without inducing mechanical and thermal distortion
  - Requires only simple fixturing
- A single tool assisted with multi-head accessories qualified for multimode machining [4, 5]
- Broad range of part sizes and thicknesses from macro to micro scales[6]
- Nozzle does not in direct contact with the work piece - no heat and mechanical induced tool wear
  - A preferable near-net shaping tool to machine difficult materials such as hardened steel and alloys

[1]The MicroMAX was named a Finalist of the 2016 R&D 100 Awards (https://www.sbir.gov/node/130 8555).

- Cost effective with fast turnaround for both small and large lots
- Amenable to micromachining and 3D machining [7 - 9]

Considerable efforts were devoted in applying waterjet for R&D and rapid prototyping with emphasis on meso-micro machining using the MicroMAX to broaden its applications for a wide range of industrial, biomedical, and military applications. Specifically, we have collaborated with several academic and research institutes, including the Massachusetts Institute of Technology – MIT (the Mechanical Engineering Department, the Hobby Shop, and the Center for Bits and Atoms - CBA), Ryerson University, Pacific Northwest National Laboratory (PNNL) under the Advanced Technology Program (ATP) for small businesses, NASA Jet Propulsion Laboratory (JPL), and others.

The collaborations have led to the discovery of interesting findings, part of which has demonstrated several unique capabilities of waterjet for meso-micro machining and others deserve further investigation.

One of the collaborations with MIT was to apply waterjet to machine nonlinear load cells with 1% of sensitivity and five orders of magnitude in force range (MIT U.S. Patent #20150233440). There were two versions of the load cells, constituting of four constant-width and tapered flexures, respectively [10]. The load cells were made from 6.35 mm thick, 6061 T6 aluminum. The novel geometries of the flexures presented considerable challenge to traditional machine tools. For example, the constant-width flexures were 1 mm wide with an aspect ratio of 98.3. One end of the flexure connected to the frame of load cell via a 20-mm diameter loop (3/4 of a circle).

The tapered flexures, on the other hand, reduced the width gradually from 10 mm to 0.5 mm over a ¼ perimeter of a 176-mm-diameter circle. By taking advantage of the cold cutting process with low side force exertion, the load cells were successfully cut on the MicroMAX. A Tilt-A-Jet® (TAJ) was used to cut nearly taper-free edges that were a critical factor to meet the required precision and repeatability of the load cells. The performance of the load cells was subsequently verified through several series of laboratory tests at MIT [11,12].

In an attempt to demonstrate the versatility of waterjet for meso-micro machining, we began conducting cutting tests of reference miniature parts using several machine tools. During the past five years, we chose three to four reference parts that were cut with lasers (CO_2 and solid-state), wire EDM, μAWJ, and CNC milling available at OMAX's R&D machine shop and Waterjet Demo Lab as well as CBA's Digital Fabrication Facility (Refer to Section 2.3 for specifications of these tools). Since 2014, OMAX collaborated with CBA to conduct test cutting using lasers and the wire EDM to compare their performances with that of the μAWJ. The test results have helped demonstrate certain aspects of the μAWJ as a versatile meso-micro machining tool and several pros and cons of lasers, wire EDM, and CNC milling.

The machining of a set of aluminum flexures used on the microsplines of the prototype asteroid gripping device under development at NASA/JPL for the Asteroid Redirection Mission (ARM) program. The spring-like flexures consisting of 11 flexure elements were cut from a 3.2 mm thick, 6061 T6 aluminum sheet. The length and width of the flexure elements were 36.3 mm and 0.5 mm, respectively. The separation between each element was 0.76 mm. The aspect ratio was therefore 72.6. Such large-aspect-ratio thin flexures presented considerable challenge to traditional machine tools. The MicroMAX, again, was applied successfully to machine the set of flexure using similar parameters described above [4].

The interesting results presented in this paper prompted the initiation of a MicroCutting Project at CBA. The main objective was to expand the scope in comparing the performances of a collection of machine tools available at CBA and other facilities. A reference part was chosen among the flexures on the NASA/JPL microsplines of the prototype asteroid gripping device. A separate paper is under preparation to document the MicroCutting Project.

TECHNICAL APPROACH AND EQUIPMENT

Technical Approach

A collection of machine tools available at OMAX, CBA, and other facilities were selected to machine reference parts that were successfully machined on the MicroMAX configured for meso-micro machining.

These parts, machined from materials that were most suitable for the individual tools, were then inspected qualitatively and quantitatively to compare the performances of these machine tools.

Micro-Abrasive Waterjet Technology

The AWJ is amenable to micromachining as the diameter of the AWJ can reduce to micro scales [7]. The μAWJ technology was developed and commercialized under the support of an SBIR Phase II/IIB grant. Several novel processes were developed and incorporated into the MicroMAX for meso-micro machining of 2D and 3D parts (https://www.omax.com/sites/default/files/product/specsheets/600091h-micromax.pdf). In essence, the main push was to downsize the AWJ nozzle capable of meso-micro machining. As such, several challenges were present as the three-phase, supersonic slurry flow inside the nozzle transitions from a gravity-dominated flow to a microfluidic flow. Novel processes and apparatus were developed to enable μAWJ technology for industrial applications.

- The flow of fine powders generates static charges that prevent consistent abrasive feed to the nozzle (establishment of adequate grounding is required to avoid the buildup of static charges)
- The drag of the microfluidic slurry forced through the mixing tube increases as the -4 power of the ID (Hagen-Poiseuille flow)
- The mean particle size of abrasives must reduce accordingly (< 1/3 mixing tube ID) to avoid clogging of the mixing tube by bridging of two large particles).
  - Fine powders of abrasive do not flow well under gravity feed (developed novel process and apparatus to improve flow ability and gravity feeding
- Alignment of the orifice and the mixing tube becomes increasingly critical with the nozzle downsize (developed proprietary apparatus to fine tune alignment of the orifice and the mixing tube)
- The Venturi vacuum downstream of the orifice decreases with the decrease in the orifice ID and the vacuum level becomes inadequate to entrain all the abrasives fed from the hopper particularly in low pressure piercing and cutting (developed vacuum assist to mitigate nozzle clogging)
- Challenges to fabricate miniature mixing tubes with the optimum aspect ratio (length-to-ID ≳ 120)

At present, the 7/15 nozzle with an orifice and a mixing tube ID of 0.007” (0.18 mm) and 0.015” (0.38 mm) is the smallest production nozzle whereas the 5/10 nozzle is currently under beta testing. An R&D nozzle with a 3/8 combination is being tested. Garnet with 240 mesh and finer can be readily used with these nozzles. For garnets finer than 240 mesh, a proprietary process was developed to enhance their flow ability. Success in developing the μAWJ technology led to the culmination in the release of the MicroMAX as a new product debuted in 2013. It has a position accuracy and repeatability of ±15μm and ±5μm, respectively. A MicroMAX version II with the incorporation of a Rotary Axis for machining ax symmetric features was released for production in 2016.[1]

Machine Tools and Participants

The participants in the performance comparison of meso-micro machining included OMAX (www.omax.com) and MIT/CBA (www.cba.mit.edu). Available machine tools used for the project included:

CBA Digital Fabrication Facility (http://cba.mit.edu/tools/index.html)

Beam Dynamics Model LMC10000 CO_2 laser system – 1.2 mx 1.2 m cutting area, 30.5 m vertical travel, 500w (1550W peak), 25 μm overall accuracy, 51 m/min max cutting speed (91 m/min traverse speed)

Sodick SL400G Wire EDM – X, Y, Z Axis Travel, 400 x 300 x 250 mm; Wire Diameter Range: 0.051 to 0.30 mm.

Oxford Solid State Micromachining Laser - 532nm diode-pumped solid-state laser, 150mm XY travel, 50 mm Z travel, 1 micron resolution. It has spot size of approximately 20 microns. The laser outputs approximately 6W of power at 10 kHz and can quickly cut through materials typically up to 0.5mm thick. It's used for fine cutting, ablation, engraving, and marking.

OMAX Corporation

MicroMAX – A MicroMAX equipped with a TAJ, a Rotary Axis, and a Precision Optical Locator (POL) is available at the OMAX Demo Laboratory (https://www.omax.com/omax-waterjet/micro max). For meso-micro machining, the 7/15 and 5/10 nozzles have been used routinely for cutting demo parts and conducting in-house R&D.[2] The nozzles were driven by an Enduro MAX 30 hp crankshaft pump (Model 4060V) with pressures up to 410 MPa. For these small nozzles, an excess flow control valve was installed to drain a part of the water through the high-pressure pump to prevent dead heading. CNC Mill - One of the CNC milling machines (Haas UMC750) with an

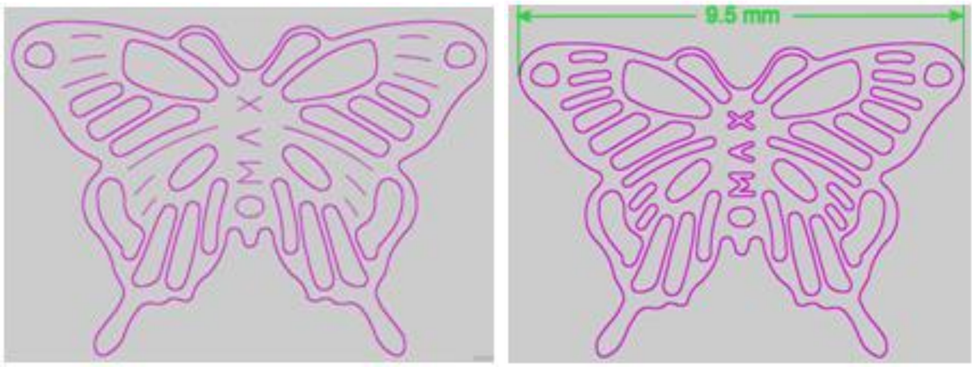
[2] The 7/15 and 5/10 nozzles consist a diamond orifice and mixing tubes with IDs of 0.007” (0.18 mm) and 0.015” (0.38 mm) and 0.005” (0.13 mm) and 0.01” (0.25 mm), respectively

end mill made by Alu-Power (36573-E5982016) at OMAX R&D machine shop was used to machine the constant-width and tapered flexures of the nonlinear load cells developed at MIT. The objective was to demonstrate whether the relative large side force exerted by the end mills on the workpiece would lead to mechanical distortion on the large-aspect-ratio flexures.

Microscope

The OMAX R&D laboratory is equipped with a Leica stereomicroscope (Model 205C) with a Model 450C camera. A PC-based ImagePro Insight Ver. 9 was installed for image inspection, recording, and analysis. The Insight software has several functions for image enhancement and precision measurements.

Micrographs with high resolution of miniature parts with minimum distortion can be captured. A stitch function is available to further boost the resolution of micrographs. Small features can be measured on the micrographs accurately.



a. Tool path for μAWJ (5/10 nozzle) *b. Tool path for solid-state laser*

Figure1. *Two versions of tool path of miniature butterfly for cutting with waterjet and solid-state laser*

Results

This section presents the test results to compare the performance of the machine tools applied to cut the miniature butterflies, tweezers, and nonlinear load cells. For the aluminum flexures developed at NASA/JPL and used on the micro splines of the prototype asteroid gripping device, only the waterjet-machined samples are presented for inspection and evaluation. A separation paper will document the work performed under the MicroCutting Project in which an extensive set of machine tools was applied to cut the flexures as the reference parts. The performance of these tools will then be inspected and compared in detail.

Miniature Butterflies

In the past five years, OMAX collaborated with CBA to conduct test cutting of microparts to compare the performances of lasers and waterjet. One of the reference parts was a miniature butterfly cut from thin titanium and stainless-steel sheets. The butterfly, consisting of slots separated by thin webs, was originally designed for large nozzles. Trepanning was set up to cut the slots. When it was downsized for the 5/10 nozzle, the width of several slots became narrower than the kerf width of the nozzle (0.28 mm). The tool paths of those slots and the OMAX logo were then changed from trepanning to slitting, as represented by the dashed curves in Figure 1a. Figure 1b illustrates the tool path of the butterfly for the solid-state laser. All the slots and the OMAX logo were cut in the trepanning mode as the spot size of laser is approximately 50 μm and was capable of negotiate the sharp corners and turns of the tool path.

Figure 2 illustrates three photographs of butterflies cut with the CO_2 laser (a), the solid-state laser (b), and the waterjet (c). The CO_2 laser failed to cut the titanium butterfly (1.3 mm thick with a span of 10 m) as its intensive heat simply evaporated the closely packed thin webs[2, 3].

Subsequently, the butterfly (0.25 mm thick stainless steel) was machined successfully with a solid-state laser pulsed at 5 KHz. The high-frequency pulsation reduced the average cutting power of the solid-state laser to minimize the heat damage to the part. It took the laser about 60 min to cut the butterfly. As a cold cutting tool with low side force exertion on the workpiece, the waterjet on the MicroMAX using a 5/10 nozzle with 240 mesh garnet (mean particle size ~ 60 μm) cut the butterfly (0.5 mm thick stainless steel) in 2.2 min. The ratio of the cutting time of the laser and the waterjet is about 27.

Figure2. *Miniature butterflies cut with lasers and waterjet [3]*

Comparison of the butterflies shown in Figures 2b and 2c clearly demonstrates the superiority in the spatial resolution of the laser to that of the waterjet.

In particular, the kerf width of the laser-trepanned OMAX logo and the narrowest slots are considerably narrower in Figure 1b than the waterjet-slit counterparts in Figure 1c. Figure 1d shows the micrograph of the waterjet cut butterfly using a 3/8 nozzle. The slots cut with slitting display a "dumpbell" shape. The oversized end points are the result of too long a dwell time during piercing and exiting. Reducing the dwell time will minimize the oversize.

In Figures 2e and 2f the tool paths shown in Figure 1a and 1b are superimposed onto the photograph of the laser-cut butterfly and the micrograph of the waterjet-cut counterpart. Figure 2f shows that the match between the tool path and the waterjet-cut butterfly is excellent.

Note that However, a slight mismatch is observed in Figure 2e between the two. A part of the mismatch could be attributed to the distortion of the camera lens.[3] No attempt was made to machine the butterfly with the wire EDM as its geometry required many re-threading of the wire to cut all the slots.

Tweezers

The same sets of tools were applied to cut miniature titanium tweezer, with the length and thickness of 35.8 and 0.89 mm, respectively. Figure 3 illustrates the tool path (3a) and the micrographs of the miniature tweezers cut with a 7/15 nozzle on the MicroMAX (3b) and the CO_2 laser (3c). Three views of the tweezers, top, side, and back, are shown for waterjet (b1 through b3) and laser (c1 through c3). Note that for waterjet cutting at the highest edge quality of 5 or Q5 was used.

The TAJ was not activated as it is ineffective for compensating edge taper on such a thin material. There is a small edge taper together with a small edge rounding on the jet entry surface of the part. Cutting was conducted with the tool path turned upside down.

[3]The photographs in Figures 2b (2e) and 2c (2f) were captured with a camera and a microscope, respectively.

Figure3. *Miniature tweezers cut with µAWJ on MicroMAX and CO_2 laser*

As such the slight edge rounding shows up on the back view (b3) rather than on the top view (b1). The micrographs of the back view were flipped about the horizontal axis. Both the edge rounding and the edge taper result in the appearance of slight narrower widths of elements on the back view than on the top view.

As a cold cutting tool, the µAWJ-cut tweezers shows no sign of heat damage. The excessive heat generated by the CO_2 laser, on the other hand, causes significant heat damage ranging from discoloring, warping to the presence of excessive amount of slag (b1 through b3). The tool path of the tweezers, the yellow curves, was overlaid on the µAWJ- and CO_2-cut counterparts, as illustrated in c1 and c2. The µAWJ-cut part appears to be slightly undersized by an average size of 0.05 mm. Two factors attribute to the under-sized cutting. The first factor corresponds to the tool offset that was set slightly larger than one-half of the actual diameter of the µAWJ.[4] The second factor is due to the finite size of the diameter of the µAWJ (0.4 mm). The first factor is responsible for the overall undersize of the µAWJ-cut part whereas the second factor demonstrates the inability of the µAWJ to negotiate the sharp corners and turns of the tool path. Since the beam diameter of the CO_2 laser is about four times smaller than that of the µAWJ diameter, it negotiates the sharp corners and turns well.

[4]The tool offset must increase to take into account the continued wear of the mixing tube by the high-speed slurry moving through it.

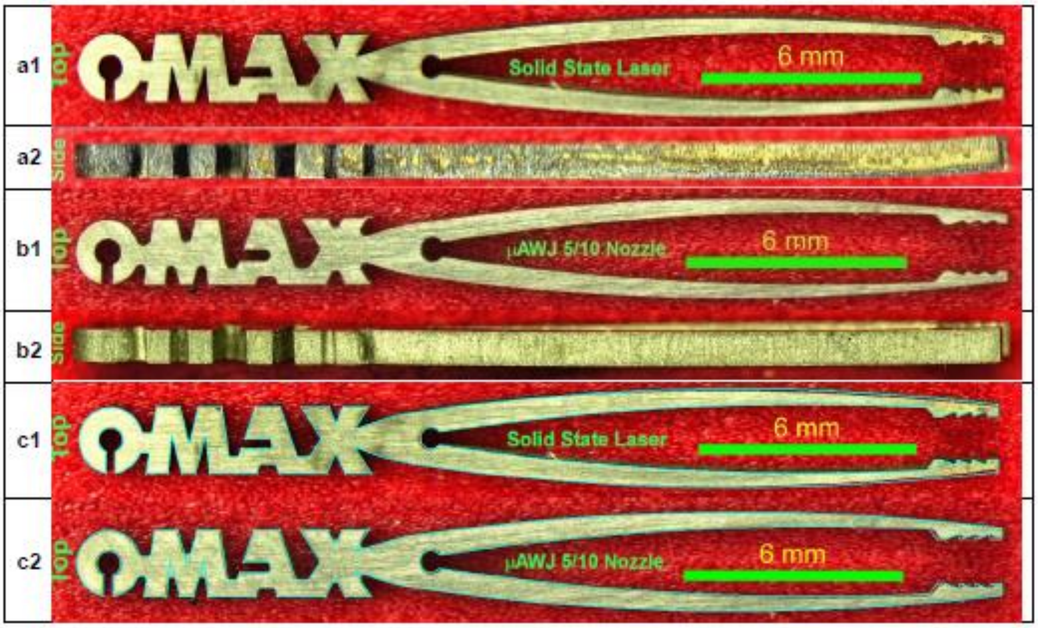


Figure4. *Micrographs of miniature Ti tweezers cut with solid-state laser and µAWJ with a 5/10 nozzle*

Subsequently, a pair of further downsized tweezers was cut with a solid-state laser, as shown in Figures4a1 (top view) and 4a2 (side view). For comparison, the same tweezers cut with the µAWJ using a 5/10 nozzle with 240 mesh garnet are shown in Figures4b1 and 4b2.

The length of the tweezers was scaled down to 25.3 mm. By pulsing at 5 kHz, the solid-state laser reduces significantly its cutting power and therefore the heat generation during cutting, leading to minimizing the heat damage to the tweezers.

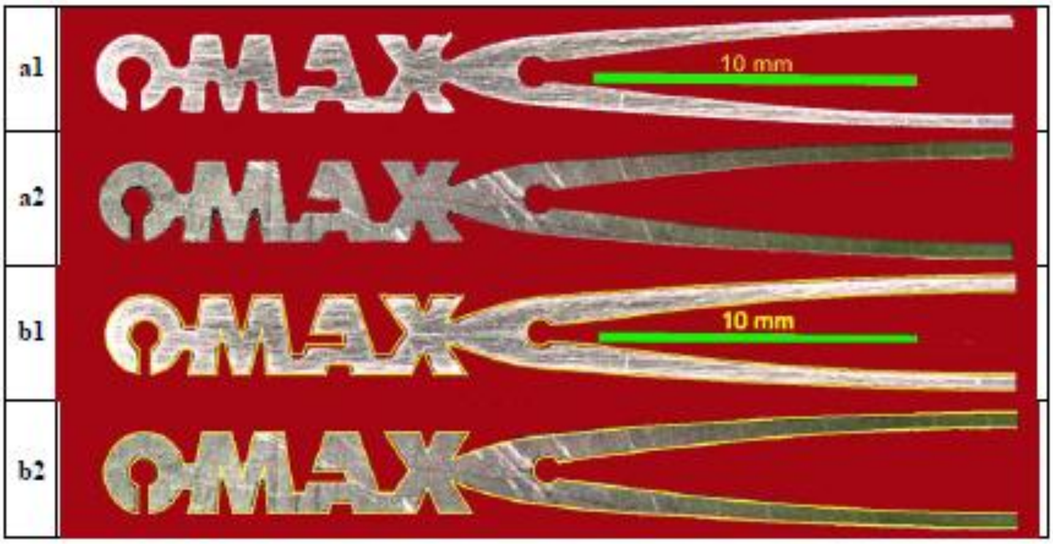


Figure5. *Micrographs of Ti tweezers cut with µAWJ (7/15 nozzle) and wire EDM (µ0.15 mm)*

However, the time to cut the tweezers has increase to 3 hours, as compared to 45 s for the µAWJ, a ratio of 240. It is expected that optimization of the laser cutting process could reduce the ratio to about 100.

Even pulsed at 5 KHz, the moderate heat generated by the laser still induced some discoloring on the edges of the tweezers, as observed in Figure 4a2, leading to a minor distortion at the end tip of the tweezers. The µAWJ diameters generated by the 5/10 and 7/15 nozzles are under 0.3 and 0.4 mm, respectively. It is evident that the 5/10 nozzle negotiates sharp corners and turns better than the 7/15 nozzle does. Refer to Figures 4b1 and 3a1 to see the difference. Furthermore, the solid-state laser has a beam diameter of ~ 0.05 mm, the capability of negotiating sharp corners and turns is better than that of the CO_2 laser and the µAWJ.

Overlay of the corresponding tool path to the solidlaser and μAWJ cut tweezers are shown in Figure 4 c1 and c2, respectively. The match bewteen the tool path and the tweezers cut with the solid-state laser and the μAWJ with the 5/10 nozzle has improved considerably. The same tweezers shown in Figure 3 was cut with a wire EDM process. Figure 5 illusstrates the micrographs of two tweezers cut with the waterjet (7/15 nozzle) and the wire EDM using a 0.15 mm diamete wire, as illustrated in a1 and a2, respectively. When operating under normal conditions, EDM, a thermal cutting, also induces a HAZ on the cut edges of the tweezers. Using the fine wire reduced the cutting power and therefore the cutting speed considerably. As such it took 38 minutes to cut the tweezers. The cutting time for the waterjet was 32 seconds. In othe words, the AWJ cut about 70 times faster than did the wire EDM. Since the wire diameter is nearly 3 times finer than the AWJ diameter, the cutting accuracy of the EDM is better than that of the AWJ. It is evident from the overlay of the tool paths onto the μAWJ- and EDM-cut tweezers, Figures 5b1 and 5b2 The the wire EDM negotiates the sharp corners and turns better than does the μAWJ.

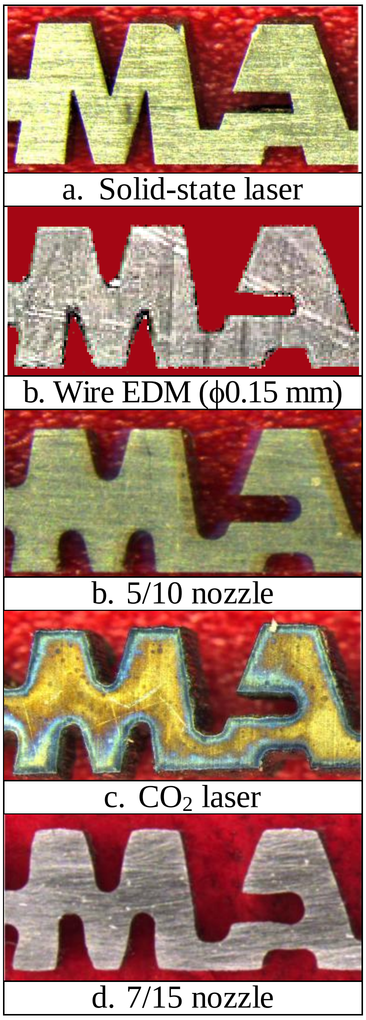
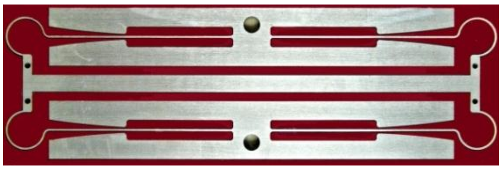


Figure6. *Kerf width achievable by machine tools*

Figure 6 shows top views of zoomed-in images of the "MA" characters extracted from the micrographs illustrated in Figures 3 through 5. The kerf widths achievable with the machine tools can be visaulized according to how well the tools negotiatethe sharp corners and turns. The narrowed the kerf, the better the match between the tool path the machined part, is demonstrated from Figure 3. The figure shows that the solid-state laser achieved the narrowest kerf width followed by the wire EDM, the 5/10 nozzle, the CO_2 laser and the 7/15 nozzle. The kerf widths for the 5/10 nozzle and the CO_2 laser are nearly the same. In the presence of the waist at the focal points of lasers, the excellent kerf width is attainable for very thin materials, say < 1 mm. It is certain increase with the increase in the part thickness.The kerf width of wire EDM does not change materially as the wire diameter is independent of the part thickness. On the other hand, the versatile waterjet is capable of machining a wide range of part thickness; its kerf width increases only marginally with the increase in the part thickness. The presence of the HAZ causes considerable discoloring on edges of the CO_2 laser-cut tweezers. The large amount of slag left on the back side of the tweezers, as showns in Figure 3b and 3c, increases the edge roughness. Figure 6b also shows faintly several burnt marks on the edges of the EDM-cut tweezers.



a. Load cell with constant-width flexures

b. Load cell with tapered flexures

Figure7. *Two versions of nonlinear load cells [10]*

Nonlinear Load Cells

Collaboration with MIT was to machine novel nonlinear load cells (MIT US Patent #20150233440). The flexure-based load cells were highly sensitive with 1% change in the force and five orders of magnitude in the force range. There were two designs of the load cells consisted of large-aspect-ratio thin flexures with constant and variable width, respectively. For the theory and design of the loads, refer to Kluger et al. [11, 12]

The load cells were to be machined on 6.35 mm thick, 6061 T6 aluminum. It appeared that waterjet, being a cold cutting tool with low force exertion onto the workpiece, would be preferable to lasers, EDM, and CNC milling. Note that lasers were not efficient in cutting the aluminum with high thermal conductivity; EDM was expected to be too slow because it must cut via multiple passes to minimize the HAZ; and CNC milling must cut slowly to avoid the mechanical distortion of the high-aspect-ratio thin flexures.

The load cells were machined on the MicroMAX with the 7/15 nozzle using 220 mesh garnet with a mass flow rate of 45 gm/min. The pump pressure was set at 380 MPa. The TAJ was activated to enable achieving nearly taper free edges of the thin flexures, a critical factor to meet the required precision and repeatability of the load cells. Figures 7a and 7b show photographs of the two waterjet-machined load cells. Figure 7a shows the one with four constant-width (1 mm wide) cantilever flexures. Each one consists of a moment compliant “19.1 mm diameter ring” connector. The aspect ratio (length to width) of the straight section is 98.3. At low forces, the full lengths of the four flexures serve as the elements to achieve the high sensitivity. At high forces, the flexures bend and rest on the stops of the load cells.

The lengths of the sensing elements reduce to about one half of the full length enabling the load cell to measure large forces without over straining the flexures. The load cell illustrated in Figure 7b has four tapered flexures. Other than the geometry of the two flexures, the same nonlinear principle applies to both for high sensitivity and large force range. Note that the tapered flexures at the points of connection to the body of the load cell have a minimum width of 0.5 mm. The cold cutting of waterjet and its negligible side force exerted on the work piece are the keys to the success in machining such large-aspect-ratio thin and curved flexures without thermal- and mechanical-induced distortion.

To demonstrate the above advantages, the flexures with constant-width and tapered flexures were selected to be machined with CNC milling. (In reality, milling does not work to machine the actual load cells as there are gaps between the flexure and the supporting frame too narrow for the passage of the miniature end mill). The micrographs of one of the waterjet-cut and CNC-milled flexures with constant width were displayed side-by-side in Figure 8 to compare their performance. Both the jet entry side and jet exit side or bottom views of the flexures were shown in Figures 8a – 8b and 8c – 8d, respectively. The tool paths of the flexures were superimposed onto the micrographs as a means to determine whether any distortion of the flexures was induced by the two machine tools. Figures 6a and 6b show that the tool paths matched well with the waterjet-cut flexure and the frame surrounding the flexure.

Note that the only fixtures were two carpenter clamps pushing the aluminum plate against the reference square that define the x and y axes inside the water tank. The flexure was cantilevered at the anchor point where its left-hand side was connected to the frame of the load cell. It would not take much side loading or rise in temperature to deflect or warp the flexure during waterjetting. With the TAJ activated during machining, the tool paths matched well with the waterjet-cut flexure on both the two views of the micrographs.

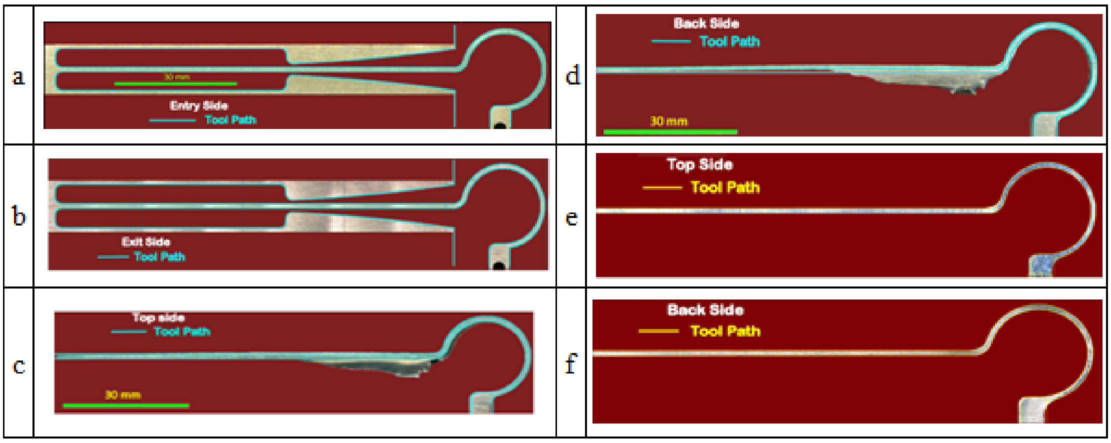


Figure8. *Constant-width flexure machined with waterjet and CNC milling*

The flexure shown in Figures 8c – 8d was milled using the Haas UMC750 with a 6.35 mm end mill on a 6.35 mm thick aluminum plate. There was, however, slight mismatch between the tool paths and the CNC-milled part, indicating that the flexure was bent slightly in the presence of the relatively high side loading and/or the increase in the frictional heat during the milling operation. In addition, the end mill did not cut through the plate between the midpoint and the beginning of the circular loop. A thin raw material was left on the bottom edge of the flexure. One of the remedies was to use a plate that was thicker than the part thickness. A second run used a plate twice the thickness of the flexure or 12.7 mm. During the milling operation, the flexure supported by a 6.35 mm thick solid base, did not bend nor warp by the side force of the end mill or the induced frictional heat. In fact, a large amount of the heat was diffused through the solid base. The flexure was then finished by milling off the solid base. Figures 8e and 8f show the finish flexure that matched well with the tool path. The remedy increased the cost of machining as the result of additional material waste and the secondary process to remove the solid base. The tapered flexures machined with the waterjet were inspected under the microscope. Figures 9a and 9b show the stitched micrograph of a portion of one of the tapered flexures (top and bottom views). The flexure with its ends tapered to a width of merely 0.5 mm and connected to the frame of the load cell was extremely delicate and flexible, more so than the constant-width counterpart. The fact that the waterjet-cut flexure matched very well with the tool path further demonstrated the importance of machining delicate features that are prone to mechanical and heat damage. CNC milling was conducted to machine one half of the left tapered flexure shown in Figure 7b. We had to modify the design to facilitate the milling operation. The modifications, as shown in Figure 9c, included the connection of the midpoint of the flexure to the frame of the load cell and to widen the gap between the flexure and the frame.

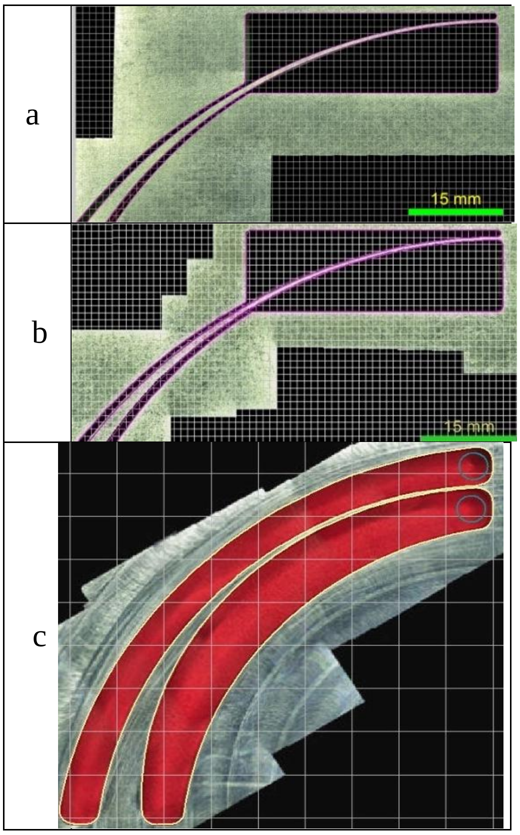


Figure9. *Tapered flexure machined with waterjet and CNC Milling*

As a result, the CNC-milled one-half of the tapered flexure matched well with the modified tool path. Without the modifications, the flexure was certain to be deflected by the side force of the end mill or the frictional heat generated during the milling operation. To sum up, the above findings indicate that it is extremely challenge and impractical, if not impossible, to machine the actual nonlinear load cells with CNC milling. The main issue is the peculiar geometry of the load cells. In particular, the narrowest gaps between the flexure elements and the supporting frames are 1.06 and 0.42 mm for the load cells with constant-width and tapered flexures, respectively. Micro-size end mills must be used to machine these load cells. They do not have the stiffness to machine the 6.35 mm thick aluminum load cells. On the other hand, lasers are not suitable for machining aluminum and EDM are too slow in order to minimize the HAZ.

Consequently, waterjet appears to be the only choice technically and economically to machine the load cells to meet the strict requirements.

Aluminum Flexures

As a part of Asteroid Redirect Mission (ARM) program, the Jet Propulsion Laboratory (JPL) of NASA has been developing prototypes of flexure-based microsplines to serve as the asteroid gripping device. The flexures consisted of a continuous spring-like element with several horizontal loops. The length of the straight segment of the loops was 36.3 mm. The width the element and the gap between the horizontal segments of the element were 0.51 and 0.76 mm, respectively. The thickness of the flexure ranged from 0.51 to 0.81 mm. The length-to-width aspect ratio was therefore 71.2. With such a large aspect ratio, the flexure was so delicate that even a small side loading exerting on the element by the machine tool during machining would cause deflection of the element, resulted in deformation of the element. The flexures were originally machined at JPL/NASA with the wire EDM that must be cut with multiple passes at low speeds to minimize the heat damage in the presence of the HAZ such as surface hardening on the cut edges and distortion of the spring-like flexure elements. In collaborating with JPL, OMAX conducted a series of tests to machine a set of aluminum flexure.

The single-pass cutting tests were conducted on the MicroMAX with the 7/15 nozzle and 240-mesh garnet. Figure 10 illustrates several AWJ-cut flexures attached to different frames together with related components.

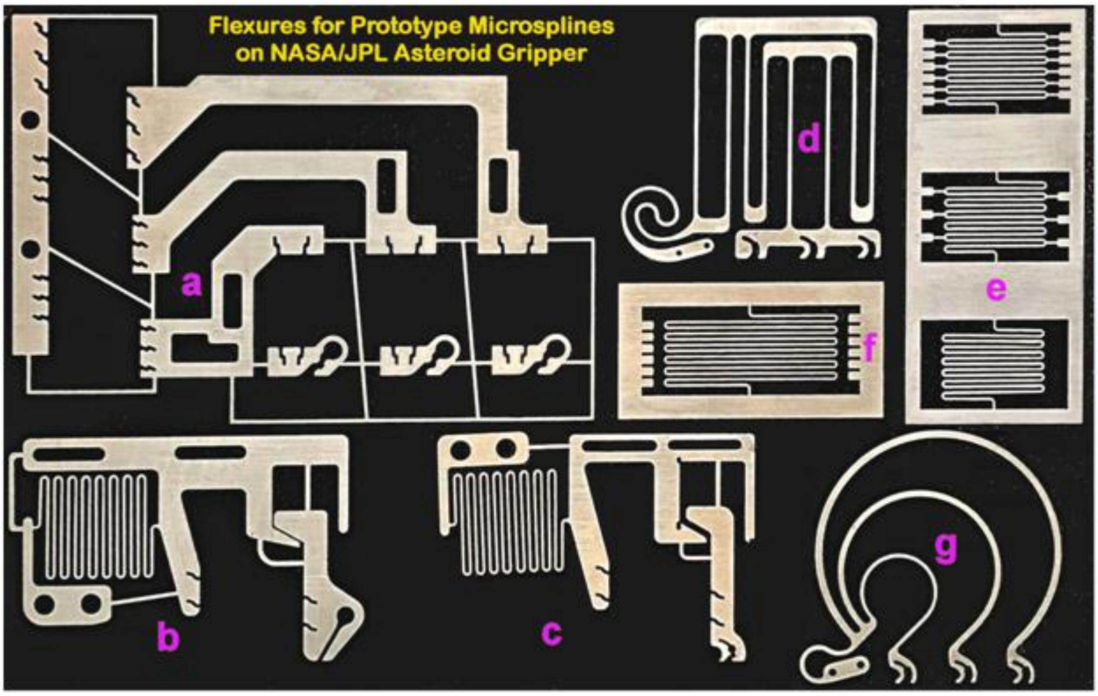
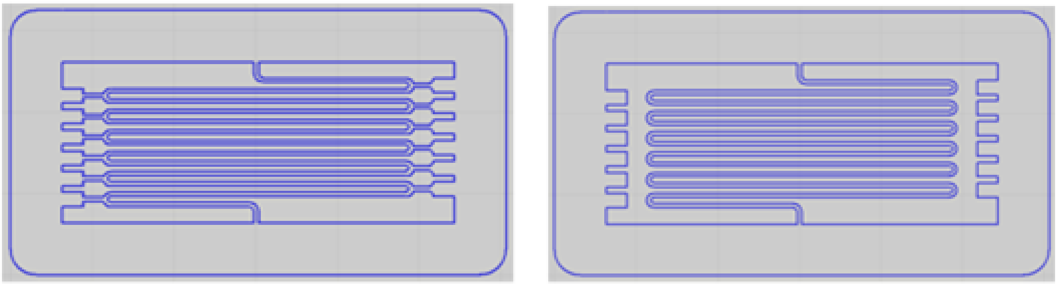


Figure10. *Aluminum flexures developed at JPL/NASA for aerospace applications [5]*

Tabs were included in several flexure designs to stiffen the structure during machining (e).The tabs were then removed after the machining of the flexures are completed (f). The flexures were attached to their frames at two ends. With the TAJ activated, the cold cutting with extremely low side force exertion is essential for cutting such flexure elements with nearly taperless edges and very little distortion. The performance of the MicroMAX also met NASA's precision requirements. Based on the times required to machine these parts, the cost ratio of the waterjet and wire EDM was 1:14, leading to a cost saving of 93% [13]. Subsequently, JPL adopted the MicroMAX as one of the primary tools to continue the development and refinement of microsplines for the asteroid gripping device.

One of the flexures shown in Figure 9f was selected to further investigate for demonstrating qualitative and quantitative performance of waterjet as a machine tool to machine such a delicate structure.

Figures 11a and 11b are two tool paths in the dxf formant with and without the tabs. A micrograph of the flexure was illustrated in Figure 12a, with the tabs removed. Figure 12b shows the superimposition of the tool path (Figure 11b) onto the flexure element. Magnified views of the two small areas in the middle and the middle-right sections of Figure 12a, were selected to compare in details the flexure element and the tool path, as shown in Figures 12c and 12d. The areas were chosen because they were farthest away from the two anchoring points and least supported. The match shown in Figure 12c is excellent. A very slight mismatch within the imaging error is observed in Figure 12d. In other words, there is nearly no macro distortion induced by the waterjet cutting process, clearly demonstrating the advantage of cold cutting and low-side-force exertion. In fact, previous papers and Sections 3.1 and 3.2 have verified that waterjet, as opposed to wire EDM, preserved the structural and chemical integrity of parent materials [13].



a. With strengthening tabs *b. Finish Flexure*

Figure11. *DXF of flexure corresponding to Figure 10f*

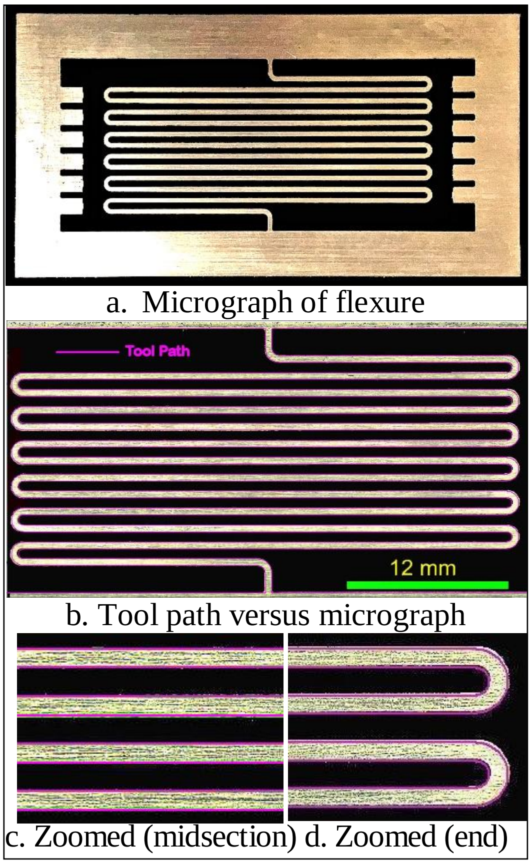


Figure12. *Aluminum flexure - MicroMAX*

DISCUSSION AND SUMMARY

With the MicroMAX released for production as the most advanced model of OMAX's Jet Machining Center, considerable experience was gained in applying μAWJ for meso-micro machining. The performance of MicroMAX using miniature nozzles, the 7/15 and 5/10 (under beta testing), was demonstrated by qualitative and quantitative comparison of miniature parts machined with several machine tools including lasers (CO_2 and Solid-State), wire EDM, and CNC milling. There are several technological and manufacturing merits of waterjet. Among them, four important merits including material independence, cold cutting, fast cutting, and minimum side loading on work pieces were demonstrated through cutting delicate parts that are difficult or even impossible to cut otherwise. Several machine tools including lasers, EDM, and CNC milling were selected to cut several common parts cut with μAWJ using two miniature nozzles, 7/15 and 5/10. Micrographs and photographs of these parts were inspected qualitatively and quantitatively to assess the performance of these tools in comparison with that of μAWJ.

The parts selected for test cutting had a couple of common features. For example, most of the parts were machined on thin materials. The aspect ratios of length-to-width or length-to-thickness were often very large. These high-aspect-ratio segments tend to deform even under weak side loading of tools and/or induced heat generated by machine tools. Waterjet as a cold cutting tool that induces minimum side loading to the work piece have shown to be most suitable for machining such parts in terms of high cutting speed, minimum part distortion, and preservation of the integrity of parent materials. Other advantages of waterjet include material independence and its capability of cutting a wide range of part thickness. It has demonstrated that the intensive heated generated by the CO_2 laser induced heat affected zone or HAZ on the cut edges of the miniature butterfly and tweezers. As a result, the thin webs on the butterfly were vaporized by the induced heat while the tweezers suffer considerable discoloring, warping, and formation of slag. In order to minimize the HAZ, the solid-state laser must pulse at high frequencies and the wire EDM must cut at very low speeds and/or with multiple passes. With the implementation of such remedies, the solid-state laser and wire EDM were able to cut at speeds over one order of magnitude slower than waterjet. Based on the comparison of the micrographs of the tweezers machined on a 0.89 mm thick titanium sheet, the achievable kerf widths of the tools were ranked accordingly. The solid-state laser (~ 50 µm spot size) achieved the narrowest kerf width followed by the wire EDM (15 µm wire), the 5/10 nozzle (250 µm jet diameter), the CO_2 laser, and the 7/15 nozzle (38 µm jet diameter). Note that the kerf width of the solid-laser in the presence of the waist at the focal point is expected to increase as the part thickness increases. The edge of parts cut with the CO_2 laser is however irregular and rough in the presence of the slag.

For the aluminum nonlinear load cells, waterjet has demonstrated as the only practical tool to machine the part. Note that aluminum was too reflective and the part thickness was too thick for the lasers whereas the extremely large length-to-width aspect ratio of the flexure presented considerable challenge to the EDM.

The geometry of the load cells also prevented the use of CNC milling as the gaps between the flexures and the supporting frame were simply too narrow for miniature end mills to pass through.

The merits of waterjet were successfully taken advantage of for machining the delicate aluminum flexures under development at JPL/ NASA for the prototype microsplines of the asteroid gripper. Waterjet was able to machine the parts about one order of magnitude faster than EDM, resulting in better than 90% saving in manufacturing costs.

The performances of the machine tools selected were evaluated by comparing the machined parts with tool paths. For the butterflies, the heat damage of the CO_2-laser-cut part was too serious to compare the two. The overall matches between the tool path and the butterflies cut with the solid-state laser and the waterjet are excellent. With a 50 µm spot size, the laser negotiates the sharp turns and corners extremely well. In order to accommodate the relatively large kerf width achievable with the waterjet (~280 µm), several slotting segments were converted into slitting.

For the tweezers, the overall matches of the tool paths with the parts machined with the lasers, wire EDM, and waterjets are all very good. The degree of the match depends on the kerf width achievable with the individual tools. Therefore, the solid-state laser has the best match followed by the wire EDM, the 5/10 nozzle, the CO_2 laser, and the 7/10 nozzle.

In conclusion, the performance of waterjet is superior to the other tools based on the preservation of material properties, cutting speed, and cost effectiveness. From the cutting accuracy viewpoint, the performances of solid-state laser and wire EDM are superior to that of waterjet. It should be pointed out that these parts will be operating under load for many cycles. Their ultimate performance will depend on their fatigue characteristics. Fatigue tests should be conducted to further evaluate the performances for their intended operations.

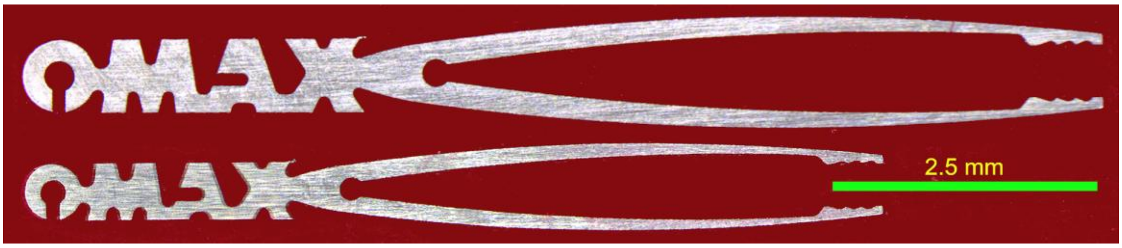


Figure13. *Tweezers machined with 5/10 and 3/8 nozzles*

The emerging AWJ technology has been advancing steadily for applications in precision micro machining. For example, the µAWJ nozzle is being further downsized toward micro machining. A research nozzle with a 3/8 nozzle combination was developed and assembled to machine miniature parts (refers to Figure 2d).

The 3/8 nozzle was also applied to machine scaled-down tweezers. Micrographs of a pair of tweezers machined with the 5/10 and 3/8 nozzles are shown and compared in Figure 13. As such the length of the tweezers reduced from 25.3 to 20.3 mm according to the diameter ratio of the two mixing tubes of 0.8. Similar reduction in the kerf width is also expected. Garnet of 240 and 320 mesh with mean particle diameters of 60 and 30 µm were used for the 3/8 nozzle. The powdery 320 mesh garnet does not flow consistently under gravity feed [14]. Proprietary processes and apparatus were developed and applied to enhance the flow ability of the fine garnet.

ACKNOWLEDGMENT

This work is supported by an OMAX IR&D project. The micro abrasive waterjet (μAWJ) technology was developed and commercialized under the support of an NSF SBIR Phase II grant #1058278.

The author would like to acknowledge the collaboration between MIT and OMAX during the course of laboratory tests comparing the performance of waterjet, lasers, and EDM. The designs of the patented nonlinear load cells were provided by Prof. Alex Slocum and it was subsequently tested by Dr. Jocelyn Kluger, Department of Mechanical Engineering.

The author would like to thank Dr. Neil Gershenfeld, Director of Center of Bits and Atoms (CBA), for the commitment of Fablab facilities for this project. Laser and EDM machining of the butterflies and tweezers were conducted by Sam Calish, Will Langford, and Christen Reed at CBA.

REFERENCES

[1] Liu HT. "7M"Advantage of abrasive waterjet for machining advanced materials, Journal of Manufacturing and, Materials Process. 2017; 1(11): 1-19. MDPI, Basel, Switzerland Available from http://www.mdpi.com/2504-4494/1/1/11/pdf.

[2] Liu HT.Versatility of micro abrasive waterjet technology for machining nanomaterials. In: Dekker Encyclopedia of Nanoscience and Nanotechnology. Third Edition.2017; ENN3-120054064: 1-18. Available from: DOI: 10.1081/E-ENN3-120054064.

[3] Liu HT. Precision machining of advanced materials with abrasive waterjets.IOP Conf. Series: Materials Science and Engineering, 164. 2017; 012008. Available from: http://iopscience.iop.org/article/10.1088/1757-899X/164/1/012008/pdf

[4] Liu HT, Cutler V, and Webers N. Recent advancement in abrasive waterjet for precision multimode machining. In: Proceedings of the 24th International Conference on Waterjetting, 2018; September 5-7 2018, Manchester, UK: BHR Group.

[5] Liu HT, Cutler V, Raghavan C, Miles P, Webers N. Advanced abrasive waterjet for precision multimode machining. In: Anna Rudawska (ed.), Abrasive Technology – Characteristics and Applications**, Intech Open Publisher; 2018;** p. 39-64. ISBN 978-953-307-906-6. Available from: https://www.intechopen.com/books/abrasive-technology-characteristics-and-applications/advanced-abrasive-waterjet-for-multimode-machining

[6] Liu HT, McNiel D. Versatility of waterjet technology: from macro and micro machining for most materials. In: Proceedings of the 20th International Conerence on Waterjetting, 2010; 20–22 October 2010, Graz, Austria: BHR Group.

[7] Miller DS. New abrasive waterjet systems to complete with lasers. In: Proceedings of the 2005 WJTA Conference and Exposition, Houston, Texas, August 21-23 2005. Paper 1A-1

[8] Liu HT, Schubert E. Micro abrasive-waterjet technology. In: **Mojtaba Kahrizi, (ed.)** Micromachining techniques for fabrication of micro and nano structures. INTECH Open Access Publisher, *ISBN* 978-953-307-906-6, 2012; P. 205-34. Available from: http://cdn.Intechweb.org/pdfs/27087.pdf.

[9] Liu HT, Olsen JH. Application of AWJ for 3D machining. In: Proceedings of the 2013 WJTA-ICMA Conference and Expo, September 9-11 2013, Houston, Texas.

[10] Liu HT Advanced waterjet technology for machining curved and layered structures. Curved and Layered Structures. 2019; 6: 41-56. Available from: https://doi.org/10.1515/cls-2019-0004.

[11] Kluger JM, Sapsis TP, Slocum AH. High-resolution and large force-range load cell by means of nonlinear cantilever beams. Precision Engineering. 2016; 43: 241–256

[12] Kluger JM, Slocum AH, and Sapsis TP. Ring-based stiffening flexure applied as a load cell with high resolution and large force range. ASME Journal of Mechanical. Design. 2017; 139 (10): 1035011-1-03501-8, Available from: DOI:10.1115/1.4037243.

[13] Liu HT, Hovanski Y, Caldwell DD, Williford RE. Low-cost manufacturing of flow channels with multi-nozzle abrasive-waterjets – a feasibility investigation. In:Proceedings of the 19th International Conference. On Waterjetting. 2008; 15 – 17 October 2008; Nottingham, UK. BHR Group.

[14] Prescott JK, Barnum RA. On powder flow ability. Pharmaceutical Technology. 1999; 24 (10): 60-84.

APPENDIX

TableA1. *Performance Comparison Machining Miniature Butterflies (Figure 2)*

Machine Tools	Material/THK (mm)	Span (mm)	Tool/Particle Sizes	Position Accuracy/ Resolution	Setup Time (min)	Cutting Time	HAZ	Damage (Mechanical/Heat)	Comments
MicroMAX [5/10][1]	SS/0.25	10	ϕ0.3 mm/30 µm	±12 µm	~ 10	2.2 min	No	No	Jet diameter > laser spot
CO_2 laser	SS/0.5	10	ϕ25 µm	50µm	~10	~	Yes	Yes	Material vaporized
Oxford solid-state laser	SS/0.25	10	ϕ20 µm	50 µm	~20	60 min	Yes	Discolored and slight distortion	Pulsed at 5 kHz

[1]Nozzle combination [orifice ID/mixing tube ID in thousandth of inch]

Table A2. *Performance Comparison – Machining Miniature tweezers (Figures 3 through 5)*

Machine Tools	Material /THK (mm)	Part Length (mm)	Tool/Particle Sizes	Position Accuracy/ Resolution	Setup Time (min)	Cutting Time	HAZ	Damage (Mechanical /Heat)	Comments
MicroMAX [7/15]	Ti/1.3	14	ϕ0.4 mm/60 µm	±12 µm	~ 10	32 s	No	No	Jet diameter > wire diameter > laser spot
CO_2 laser	Ti/1.3	14	ϕ25 µm	50µm	~10	~ 1 min	Yes	Yes	Discolored and warped with excessive slag
Wire EDM	Ti/1.3	14	ϕ0.15 mm	15 µm	~20	38 min	Yes	Discolored	Cut at reduced speed
MicroMAX [5/10]	Ti/0.9	10	ϕ0.3 mm/30 µm	±12 µm	~ 10	45 s	No	No	Jet diameter > wire diameter > laser spot
Oxford solid-state laser	Ti/0.9	10	ϕ20 µm	50 µm	~20	3 hrs	Yes	Discolored	Pulsed at 5kHz

Table A3. *Performance Comparison – Machining Nonlinear Load Cells (Figure 6 through 7)*

Machine Tools	Material/THK (mm)	Part Length/ width (mm)	Tool/Particle Sizes	Position Accuracy/ Resolution	Setup Time (min)	Cutting Time (min)	HAZ	Damage (Mech)	Comment/Remedy
MicroMAX [7/15][1]	AL/6.4	121/1.0	ϕ0.4 mm/60 µm	±12 µm	~ 10	6.5	No	No	TAJ was activated to remove edge taper
Haas UMC750	AL/6.4	121/1.0	ϕ3.2 mm	~	~20	14	No	Yes	Not suitable for milling the actual load cells as end mill diameter > gap between flexure and frame. Increased thickness of blank to minimize distortion

Citation: *(Peter) H.-T. Liu, "Performance Comparison on Meso-Micro Machining of Waterjet, Lasers, EDM, and CNC Milling", International Journal of Emerging Engineering Research and Technology, 7(6), 2019, pp.31-46*