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Waterjet Technology for Machining Fine Features Pertaining to Micromachining

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Waterjet Technology for Machining Fine Features Pertaining to Micromachining

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Abstract

Abrasive-waterjets (AWJs) using several orifice/mixing tube ID ratios and waterjets (WJs) were applied to machine fine features pertaining to micromachining. A number of geometric features and font sets were machined on thin metal and nonmetal sheets to evaluate the performance of the jets for micromachining. Test results show that the minimum kerf width of slots machined with the AWJs and WJs were about 300 and 150 μm , respectively. When machining ribs, the width could be thinner than that of slots. The minimum width of ribs is primarily limited by the stiffness of the parent material. On the contrary, the minimum kerf width of AWJ-machined slots is limited by the smallest orifice/mixing tube ID ratio that can be used without clogging the nozzle, as the Venturi-generated vacuum weakens with the decrease in the waterjet diameter under the same operating pressure. An ejector connected to the mixing chamber of the nozzle helps to reduce clogging and therefore facilitate further downsizing the ID ratio. For softer materials or thin metals such as aluminum, the kerf width of WJ-machined slots is smaller than that of the AWJ-machined ones. The edge quality of slots machined with WJs is however inferior to that machined with AWJs, as WJs leave a large amount of frays along the cut edges. To further reduce the kerf width of AWJ-machined slots, a novel process, SAWS, was developed to work in tandem with AWJs. Preliminary test results are presented to demonstrate the superiority of the AWJ/SAWS to conventional AWJs for micromachining.

1. Introduction

There has been considerable demand for a cost-effective and fast turnaround machine tool for various industrial applications from art and craft, jewel and watch making, to semiconductor singulation. Versatility is one of the key selection criteria although the required specifications in terms of precision, surface finish, process induced degradation, and other factors vary. With the advent of asserted research and development in micro/nano technology, industrial and consumer products derived from this technology is expected to become commercially available in 5 to 10 years. It is anticipated that the demand for low-cost micromachine tools would increase considerably as their availability would make these products more affordable. These tools will be applied for machining micro devices or parting components produced with micro/nano technology. Development of a versatile tool that is material independent and capable of preserving the structural integrity of multi-material components as a whole would be preferable.

Ultrahigh-pressure waterjets are one of such tools that have considerable potential for micromachining. Nowadays, waterjets have been competing on equal footing with CNC machines, lasers, EDM, and chemical etching, and ultrasound for a broad range of industrial machining. In some cases, waterjets are superior to conventional tools because of several inherent advantages:

- No heat-affected zone (HAZ) to compromise the structural/chemical integrity of machined parts [2]
- Virtually a material independent process – environmentally- and user-friendly [3]
- Minimum force exerted on parts (simple fixturing)
- No tooling – cost-effective and fast turnaround for large and small lots (for production and/or R&D)

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- Multi-machining mode - roughing, parting, drilling, turning, milling, and grooving, etc. in a single setup with no need for tool change and part transfer
- No contact tool to break when machining extremely hard and tough materials
- Amenable to stack and 3D machining
- Capable of machining high-aspect-ratio ribs/slots (through or blind) that cannot be matched with most other machine tools [2]
- Wide range in part size and thickness (from macro to micro)
- High potential for micromachining with some capabilities demonstrated [4-7]
- Compatible with “Just-In-Time” practice for lean manufacturing

Waterjets generally operate in several formats: (1) Waterjets (WJs) with no abrasive; (2) Abrasive-waterjets (AWJs) with abrasives through an entrainment process; and (3) Abrasive slurry jets (ASJs) by pumping abrasive slurry through the nozzle. The two-phase ASJ is up to five times higher in material removal rate and more amenable to micromachining than AWJs when operating at the same pressure [8]. For special applications such as cutting hydroscopic materials, liquefied nitrogen is used to replace water as the working fluid [9]. For simulation of microelectronic components such as semiconductor chips from panels consisting of multiple elements, AWJs and ASJs have been successfully applied for industrial applications [11,12]. While AWJs are operating at up to 600 MPa, ASJs are only limited to about 70 to 103 MPa in order to minimize the wear of components in the path of the highly abrasive slurry.

The potential of waterjet technology for micromachining has been discussed and demonstrated in the literature. Miller [10] demonstrated the success of using 300 and 50 nm particles in 40 μm diameter waterjets for micromachining in the laboratory. Although operating AWJs with micron diameter is possible in principle, current issues of consistency of gravity flow of fine abrasives, abrasive quality assurance and system cleanliness procedures, however, has limited AWJ diameters of 50 μm or so.

The above advantages and continued performance improvement together with the excellent market environment have presented a unique opportunity for further advancing waterjet technology to penetrate the micromachining market. The versatile waterjet machine tool could be cost effectively and expeditiously applied to fabricate components for all phase of manufacturing from R&D, prototyping, to production. As a virtually material independent machine tool, waterjets could outperform conventional machine tools that are material selective, particularly for nanomaterials that are integrated seamlessly and optimally in the molecular level. Even when the precision of waterjet technology is inadequate, it could still be used as a near-net shaping tool. Qualified tools could then be used to trim the near-net shaped parts to the final shape. Only very small amount of material will be removed during the final trimming, significantly reducing the tool wear and the frequency of tool breaking for extremely hard/tough materials.

The main objective of this paper is to demonstrate the potential of waterjet technology for micromachining and recent advancement toward the establishment of a commercially viable waterjet-based micromachining tool. As described above, the properties of waterjets are inherently superior to other machine tools. Nowadays, lasers have been used extensively for micromachining. The presence of a HAZ and induced hardened surface layer on the laser machine edges could present a problem for certain applications. Besides, materials that are highly reflective are difficult or even impossible to cut with lasers. The cold-cutting and material-independent features of waterjets are superior to lasers. On the other hand, the absence of a recast layer and fast cutting speed are the advantages of waterjets over EDM [2]. At present, the only disadvantage of waterjets is its inability to machine features finer than around 100 μm . Further technological advancements are needed in order to match the micromachining capability of lasers and other tools. One of the specific objectives is therefore to consider developing novel processes for minimizing the kerf width of waterjets to achieve micron resolution.

2. Waterjet Technology

An ultrahigh-pressure (UHP) WJ is formed by forcing pressurized tap water via a UHP pump up to 600 MPa (87,000 psi) through a small orifice. To form an abrasive-waterjet (AWJ), abrasives are entrained into the jet through a feed port just downstream of the orifice where a vacuum is created (jet pump effect). The entrained abrasives are accelerated in a mixing tube attached downstream of the feed port. The diameter ratio of the orifice and the mixing tube is typically ranging from 1 : 2 to 1 : 3. An option is an abrasive slurry jet (ASJ) that is formed by pumping abrasive slurry through the orifice; the nozzle is essentially the same as the WJ. For illustration, Figure 1 shows a drawing of a direct-drive crankshaft pump and nozzle configurations for forming UHP WJ/ASJ and AWJ.

The plungers in the pump are pushed into closed chambers to raise pressure and expel fluid through an outlet check valve; as the direction of the plunger is reversed, low-pressure fluid enters the chamber through an inlet check valve. There are two types of UHP pumps available commercially, the intensifier and crankshaft pumps. The difference between the two pumps is only the means by which the plunger moves. In both cases the continuously reciprocating plunger provides the pumping action. The crank pump uses a crank similar to the one in an automobile engine; the intensifier drives the plunger with a hydraulic cylinder, usually with oil. Nowadays, the bulky, noisy (100 dba or higher) and inefficient (70 % efficiency) intensifier pumps are being replaced by the efficient (95% efficiency) and low-noise (75 to 80 dba) crankshaft pumps for many AWJ systems.

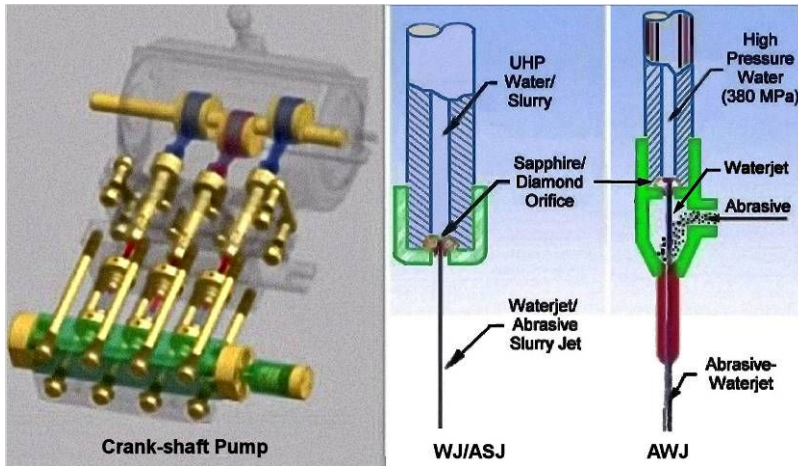


Figure 1. UHP crankshaft pump and nozzle configurations

Because of the advantages of the UHP waterjet technology, as described in the last section, the technology has become a mainstream machining tool competing in equal footing with EDM, laser, ultrasonic machining processes. For certain materials and geometries, the AWJ is found to be superior to its conventional counterparts. As a result, the UHP technology has experienced considerable growth for industrial applications since its commercialization in the 1980s [1]. Many job/machine shops are now equipped with UHP AWJ systems for a range of applications from 2D shape cutting, surface preparation, weight reduction of space-borne mirrors, and various machining tasks.

Using different formats of waterjets, Miller [4,5] investigated the potential and prospect of waterjet technology for micromachining. He compared the beam diameters of lasers and waterjets with different formats, as illustrated in Figure 2. The beam diameter of a water-only jet is also added in that figure for cutting soft materials and thin metals such as aluminum and copper. It is evident that lasers span the widest range of beam diameters from several millimeters to nearly one micron. WJs would have small beam diameter comparable to that of lasers but its applications are only limited to soft and thin materials. In the presence of water, air, and abrasives, the three-phase AWJ spreads upon exiting the mixing tube. Its beam diameter is therefore the largest. The beam diameter of the two-phase ASJ would be smaller in the absence of entrained air and the mixing tube. In principle, the beam diameter could be very small. The

limitation would be mainly due to concerns of the frequency of orifice clogging. Quality control of the abrasive size distribution would dictate the minimum size of the orifice that can be safely used without frequent clogging. At present, ASJs with pressure up 140 MPa is commercially available. The exceptional high wear on the orifice and other components in contact with the high-speed abrasives significantly reduces the operating lives of such components. Until operating lives of those components can be extended, ASJs will be limited in its operating range.

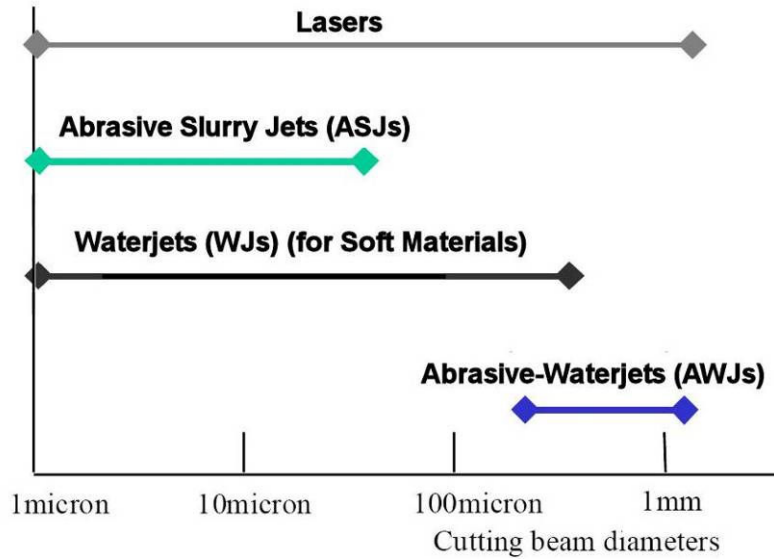


Figure 2. Comparison of beam diameters of lasers and waterjets [5]

3. Experimental Facilities and Methods

3.1 Facilities

Micromachining was conducted using an OMAX JetMachining[®] Center (JMC) – Model 2652. Figure 3 is a photograph of the JMC together with a preproduction AWJ nozzle (left) and a water-only-nozzle (right) used to demonstrate waterjet micromachining capabilities.



Figure 3. Photos of Model 2652 JMC

[®] JetMachining is a registered trademark of OMAX Corporation

To minimize the waterjet-machined features, a preproduction nozzle with nozzle combination as small as 127 μm (diamond orifice)/254 μm (mixing tube) was used.¹ For thin aluminum and copper and thin non-metallic materials, a water-only-nozzle (WON) with a diamond orifice as small as 89 μm was used. Garnet size as small as 320 mesh was used as abrasive. Garnet with size finer than 220 mesh, however, does not flow well via gravity feed. In addition, there is a short delay in developing a full vacuum in the nozzle mixing chamber as the jet on-off valve is open to allow the waterjet to flow through the orifice. In the absence of a full vacuum (i.e., weak jet pump effect), moisture/mist tends to escape momentarily and spits into the entrance of the feed tube, soaking the abrasives first arriving from the hopper. After several cycles of on-off operations of the nozzle, there is an accumulation of wet abrasives stuck to the wall of the feed tube. As a result, both the length and thickness of a wet layer of abrasives increases at the entrance end of the feed tube. This leads to an increase in resistance of the abrasive flowing through the feed tube. Eventually abrasives clog at the nozzle entrance when the flow resistance overcomes the suction created by the jet pump effect. Special feeding arrangements, such as adding an ejector to boost the vacuum level, have limited success to mitigate clogging in the abrasive feed tube at the entrance of the nozzle.

3.2 Methods of machining

The JMC is equipped with a PC-based controller operating under a “Compute first, move later” patented principle [13,14]. The JMC is run by two proprietary CAD and CAM programs. This PC-based CAD program is for designing parts, importing drawings from other CAD program, or tracing a drawing or photograph. The finished drawing will then be converted into a toolpath used to make the part. The PC-based CAM program controls the JMC to create the part from the toolpath created by CAD program. Prior to running the CAD program, the operator will have to input the type and thickness of the material from which the part will be made and the required edge quality of the part. By retrieving the machinability of the chosen material, M , from the PC memory, the CAM program calculates the exact nozzle motions required to make the whole part accurately to within 50 μm or better. Minimum operator intervention is only needed during the execution of the CAM program. Figure 4 illustrates the waterjet machinability of a collection of common industrial materials. The list has kept expanding as new entries are added continuously. Consider that the machinability shown in the figure is optimized for use with 120 and 80 mesh garnet. The machinability for garnet finer than 120 mesh would have to be adjusted accordingly.

The JMC was equipped with a 5-axis device that is capable of tilting the nozzle dynamically to machine parts with square edges. Such a device was not activated most of the time throughout the course of the investigation. As a result, there is considerable taper on the cut edges, particularly for thin materials. In fact, we took advantage of the larger taper by intentionally cutting the specimens with the toolpaths set to its mirror image counterparts. As such, the kerf width of features on the exit side of the shim is smaller than those on the entry side.

Keep in mind the kerf width determines the minimum width of slots machined with a particular ID ratio. However, there is no limitation on the width of ribs machined with AWJs/WJs. The strength and stiffness of the materials govern the minimum aspect ratio of the ribs machined with AWJs/WJs without distortion, such as bending, twisting, and/or breakage.

AWJs leave a unique striation pattern on the cut edges with their surface roughness, R_a , maximized at the jet exit side. For fatigue critical applications such as aircraft manufacturing, experiments were conducted to measure the surface roughness, residual stresses, and fatigue lives of AWJ-cut aluminum dog-bone specimens. Test results were reported in great details elsewhere [15,16]. In essence, AWJ-cut specimens were prepared with several edge qualities from a scale to five by changing the nozzle traversing speed and with and without applying secondary processes such as sanding and dry-grit blasting with 180-mesh

¹ OMAX currently has three production AWJ nozzles: MAXJET 5 [0.36 mm (orifice ID)/0.76 mm (Mixing tube ID)], MINIJET [0.25 mm/0.53 mm], and SUBMINIJET [0.18 mm/0.38 mm]. Nozzle combinations smaller than 0.18 mm/0.38 mm ID could be mounted onto the SUBMINIJET nozzle body.

Al₂O₃ abrasives. The fatigue performance of these specimens was compared with that of CNC-milled counterparts that are served as the baseline specimen. The measured fatigue lives of all specimens except that of AWJ-cut ones treated with dry-grit blasting were found to be proportional to R_a . However, when the visual appearance of the striation pattern was removed by dry-grit blasting, the fatigue life was significantly increased to be at least 3 times that of the CNC milled counterparts. It is evident that dry-grit blasting induces residual compressive stresses on the AWJ-cut edges. Residue compressive stresses are known to suppress micro-crack initiation under cyclic loading, leading to the significant increase in fatigue performance. Furthermore, garnet embedment is no longer an issue after dry-grit blasting.

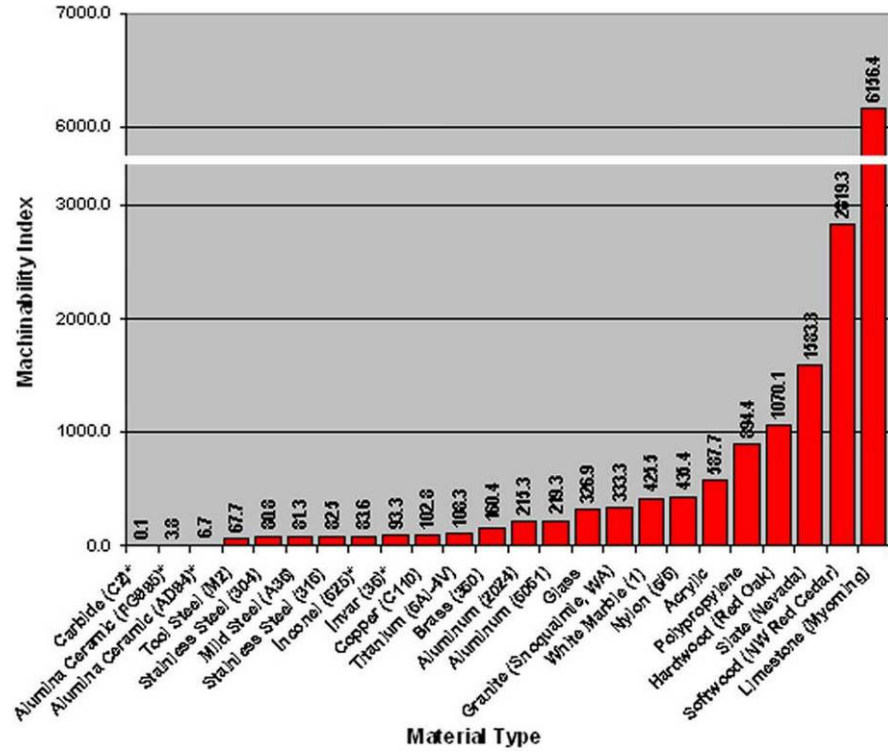


Figure 4. AWJ machinability of common industrial/engineering materials – one of the CAM’s built-in features for automation control

4. Test Results

4.1 Templates

Several templates with various geometrical patterns and font styles were designed for evaluating the micromachining performance of the SUBMINIJET nozzle using different nozzle combination and abrasive sizes. Figure 5 illustrates the drawing of a baseline template. Features and patterns on the template include thin slits (dashed lines), slots, squares and circles of different sizes, and text with different fonts and sizes.² Several templates consisting of a collection of subsets of the above features and/or text were also used. Specimens were machined from several materials with these templates to demonstrate the advantage of waterjet technology as a material independent micromachine tool. For each set of test parameters, specimens of several sizes by using templates at different scales were machined to examine the performance of a particular setup. Performance judgments were based on several factors including edge quality, kerf width, geometrical tolerance, burrs and others.

4.2 Test Results

4.2.1 Baseline Specimen

Figure 6 is an AWJ machined 0.5 mm thick stainless steel specimen using the MINIJET nozzle with an orifice/mixing tube ID ratio of 0.25 mm/0.53 mm (0.010”/0.021”) together with 220 mesh garnet and 348

² Slits and slots, by definition, were machined with a single pass and dual passes, respectively

MPa (50 ksi). The specimen was machined using the baseline template shown in Figure 5. It would serve as the reference set for comparison with others machined with different ID ratios. Figures 6a and 6b correspond to the top and bottom surfaces of the specimen; Figure 6b was viewed as the mirror image of the actual specimen to facilitate viewing the text normally. The scale shown below the images is in millimeters. Since the specimen was machined without taper compensation, there is a taper in the direction parallel to the jet axis; the thinner the workpiece, the more the taper appears. It is evident from the two images that the kerf width of the slits is slightly narrower on the bottom surface than on the top surface. If the minimum kerf width is required, the preferred method to machine the parts is by using the “mirror” option available in the CAM program.

For the scale used in Figure 6, all the geometrical patterns and text are well-defined. The minimum kerf widths of slits on the top and bottom surfaces were measured to be 700 and 450 μm , respectively. The resolution of the X-Y traverse (78.7/mm) is more than adequate to trace them truly. Note there is an option to double the resolution to 157.5/mm through software control. Besides, the jet is relatively thin when compared with the kerf width of the patterns and fonts. The scale of the template could be set in the CAM program by changing the scale factor from its default value of “1.” The CAM program will machine the workpiece according to the scale factor setting. Two limits would reach as we continue reducing the template scale. First, the kerf width would reach its limit defined by the diameter of the jet. Once the limit is reached, further reducing the template scale would not reduce the kerf width. Second, imperfections in certain details of small patterns would begin to appear, as the resolution of the X-Y traverse is inadequate to follow the details of the fine features. One of the objectives of the present investigation is to determine when the above two limits are reached for micromachining.

The CAD program has several sets of fonts available for the user to select. It is essential to choose the proper fonts for different sizes of the specimens. The fonts used in Figure 6 are the Ariel Stencil font and MIK New Roman Stencil font on the top and bottom parts of the specimen, respectively. When the scale of the template reduces, these fonts will become more and more difficult to use, as some of the characters would lose their cores (e.g., “” would appear as “” on the specimen). There are special “stick” fonts designed for machining small parts. Several “stick” fonts were tested to find the optimum font for micromachining.

4.2.2 AWJ Micromachined Specimens

The preproduction nozzle equipped with three orifice/mixing tube ID ratios (0.18 mm/0.38 mm, 0.13 mm/0.30 mm, and 0.13 mm/0.25 mm) were used to machine specimens using several templates described in Section 4.1. The specimens were examined to determine the overall appearance of the AWJ machined parts and the limit of the kerf width for each ID ratio.³

Figure 7 illustrates the specimen machined on a 0.25 mm thick stainless steel shim using a template similar to that shown in Figure 5. A different font was used in the lower left quadrant of this template. Machining was conducted using the 0.18 mm/0.38 mm ID ratio with the pump operating at 345 MPa. The abrasive was 220 mesh garnet. The scale factor of 0.5 was set in the CAM program for machining this specimen. The “mirror” option was activated in machining this specimen and Figure 7a is viewed as the

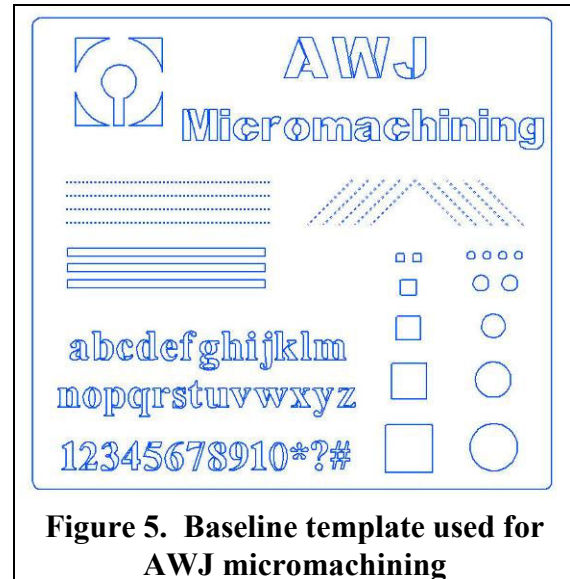


Figure 5. Baseline template used for AWJ micromachining

³ The one with the ID ratio of 0.18 mm/0.38 mm has been released as a production nozzle (SUBMINIJET nozzle – see Footnote 1) in mid 2009.

mirror image to facilitate normal reading of the text. As a result, the features in Figure 7b are more well-defined than those in Figure 7a due to the taper in the machined part. The kerf widths on the top and bottom surface were measured to be 320 and 380 μm , respectively.

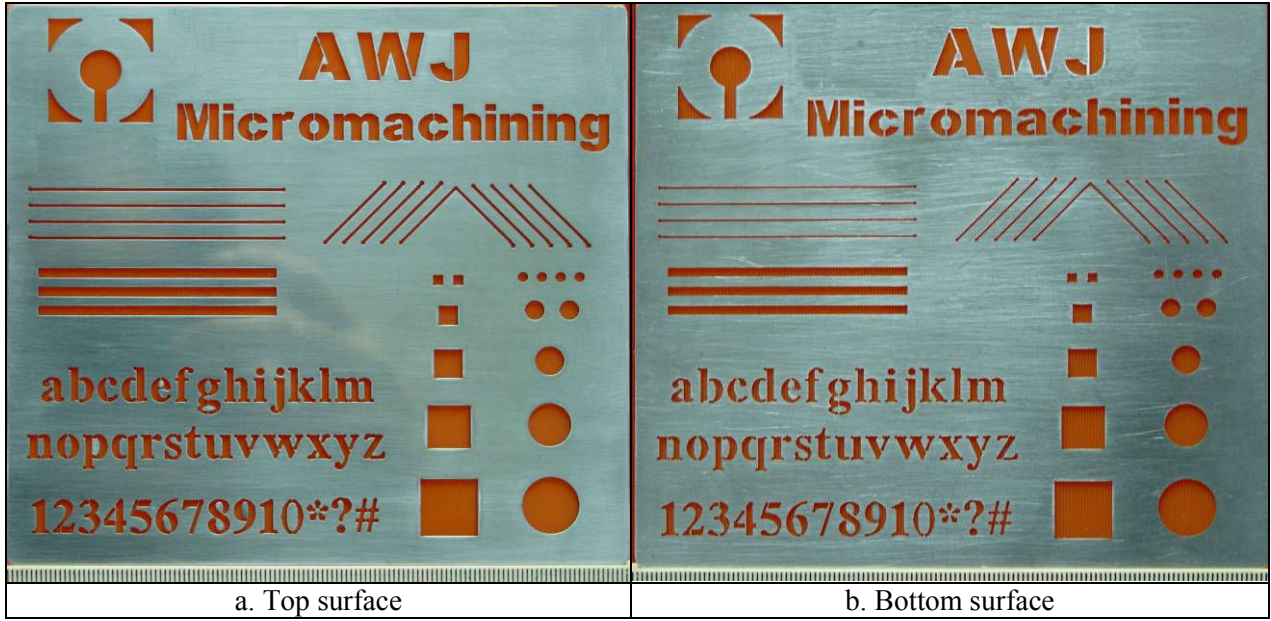


Figure 6. Baseline specimen machined on 0.25 mm thick stainless steel shim with 0.18 mm/0.38 mm ID ratio, $M \approx 80$.⁴

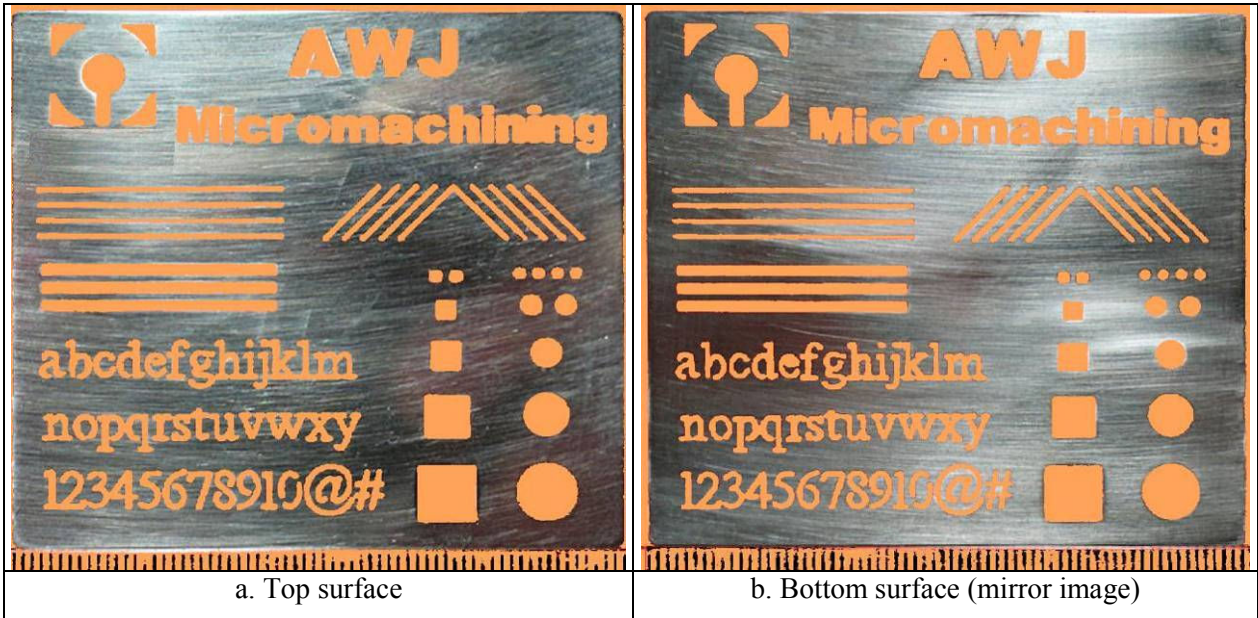


Figure 7. Stainless steel specimen machined with 0.18 mm/0.38 mm ID ratio, $M \approx 80$.

Comparison of Figure 7a and 7b show the difference in the kerf width results in larger separation between characters and crisper patterns in Figure 7b than Figure 7a. Such visual differences are, however, not as clear in the image as in the actual part.

⁴ The scale in all figures is in millimeters. The numbers in several figures are in centimeter (10 units).

The same nozzle with 0.13 mm/0.25 mm ID ratio operating at same parameters was applied to machine specimens made of 0.25 mm thick titanium and 0.64 mm thick alumina, respectively. One of the surprising properties of AWJs is it cuts titanium 25 to 30% faster than stainless steel; the corresponding machinability indices are 108 and 81, respectively. On the other hand, cutting titanium with conventional tool is often difficult. To the other extreme, alumina is one of the materials with very low machinability, i.e., $M \approx 4$.

Figure 8 illustrates the titanium specimen machined with a scale factor of 0.6 and the “mirror” option chosen. Note that the minimum kerf width (or the minimum width of slits) is governed by the ID of the mixing tube and would not change with the scale factor. The size of the features of various patterns on the specimen, however, is proportional to the scale factor.

The font of the text in the lower left quadrant again differs from those used in the other specimens. Comparison of the four fonts used in these specimens, this particular one is most suitable for machining small text; it is simple and easy to read.

Figure 9 illustrates the alumina specimen and the patterns on which differ from the others. All the text except under the logo, were removed. With the size of the logo as the reference, the equivalent scale factor is 0.5. The kerf widths were measured to be 250 μm on both surfaces. A Leica stereomicroscope (Model WILD M3B) equipped with a reticle on one of the eyepieces was used to measure the kerf width. For this specimen, a special device that dynamically tilts the nozzle to remove the taper of edges was activated, resulting in square edges. Due to low machinability, the specimen took a considerably longer time to machine. The patterns on the specimen are the most precise and appealing.

The smallest specimen was machined on a 0.25 mm thick stainless steel shim with a scale factor of 0.3, as illustrated in Figure 10. It is important to point out that the width of slits or the characters is governed by the ID of the mixing tube. It is independent of the size of the specimens. Changing the size of the specimen only changes the overall dimension of the characters and the geometry of the pattern. Visual evaluation of the images must reference to the scales of individual scales shown below the images. For features finer than the ID of the mixing tube, corners with sharp angles would not be reproduced accurately. For example, the rounding of the right-hand side corners at the two triangles of the OMAX logo is a result of the above limitation. For the same reason, certain rounding at the start and stop of a slit is also expected. Optimization of the dwell time of the jet at the stop and start of a slit could minimize the rounding to some extent.

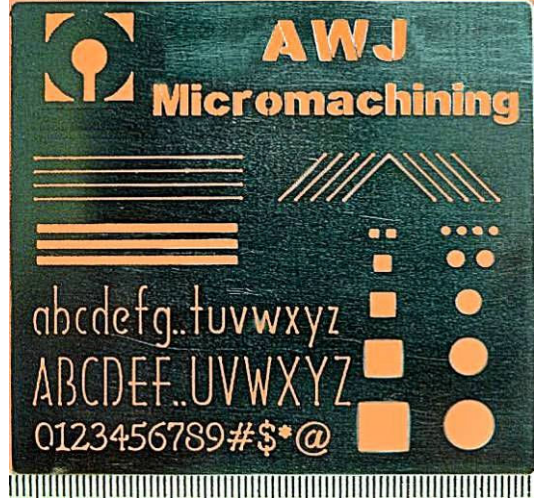


Figure 8. 0.25 mm thick titanium specimen machined with 0.13 mm/0.25 mm ID ratio ($M \approx 108$)

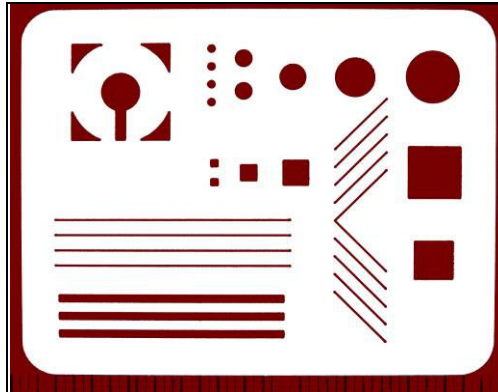


Figure 9. 0.64 mm thick Alumina specimen machined with 0.13 mm/0.25 mm ID ratio ($M \approx 4$)

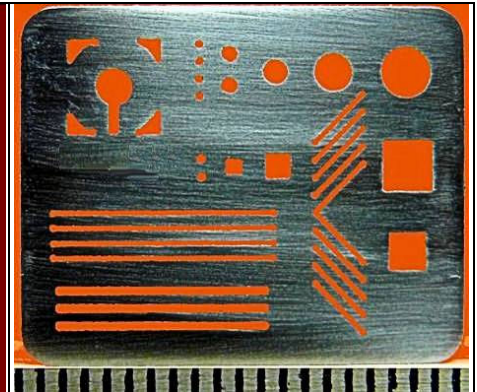


Figure 10. 0.25 mm thick Stainless steel specimen machined with 0.13 mm/0.25 mm ID ratio ($M \approx 80$)

The same nozzle was applied to machine a spiral slit on a 0.25 mm thick stainless steel shim and a miniature butterfly on a 0.25 mm thick titanium shim, as illustrated in Figure 11a and 11b, respectively. The average width of the slit in Figure 11a is about 250 μm . The thin rib of the butterfly was measured to be about 80 μm . The author has demonstrated that one of the advantages of AWJ is to machine high-aspect-ratio ribs and slots [2]. For example, the maximum aspect ratio of the thin ribs shown in Figure 11b is about 80. Such large high-aspect-ratio ribs could be very difficult, if not impossible, to machine with other machine tools. Chemical etching could be used, but it would be very time consuming and especially cost ineffective for small lots. Furthermore, chemical etching could only be applied to shims with thickness typically less than 2 mm.

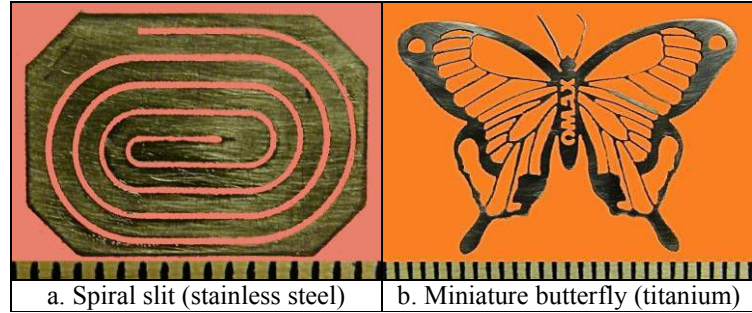


Figure 11. AWJ micromachined parts

4.2.3 WJ Micromachined Specimen

For relatively soft materials or thin metals such as aluminum and copper, a water-only-nozzle (WON) was used to machine selected fine features on them. For the WON, an 89 μm (0.0035 in) diamond orifice was used. The pump operating pressure was 378 MPa. The corresponding water flow rate is 0.19 l/min (0.05 gal/min). Figure 12 illustrates WJ-machined features on a 0.25 mm thick aluminum shim. In the absence of abrasives, material removal is accomplished by high-speed water droplets through shearing and tearing of the materials. Such a mode of material removal differs from that of high-speed and high-density abrasives of AWJs.

The WJ was also applied to cut other relatively soft materials. Figure 13 illustrates a WJ-machined specimen on a soft plastic material 0.46 mm thick, with the same features shown in Figure 10. For cutting this material, the WJ leaves frays along the cut edges. Ultrasonic cleaning removed only some but not all the frays.

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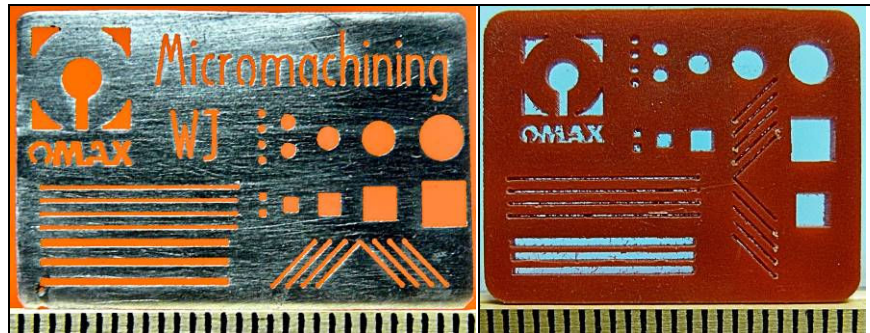


Figure 12. WJ-machined features on 0.25 mm thick aluminum, $M \approx 215$ Figure 13. WJ-machined features on 0.46 mm thick plastic, $M > 400$

4.2.4 Optimum fonts for micromachining

A collection of a number of sets of tool path fonts is available in the CAD program. Selection of these font sets could be made in the “Special Tools” menu. By selecting the “Create Text (Tool path fonts)” submenu, a description of the characters supported by the particular font set selected is given. Text is created and the characters are linked by typing supported characters on the keyboard. The text of the linked characters is displayed as they are typed. Entering the text will place the text on the CAD window. Toolpaths of the text can be generated, just like those of the drawing, by selecting the “Path” function. Different font sets could be chosen by the users for various applications. For example, stencil style font

sets are most suitable for relatively large text equivalent to the bold face. The text shown in top half of Figure 8 corresponds to the stencil style fonts. For fine text used in micromachining, several “stick” style font sets are available. These stick fonts use slitting to minimize its width facilitating tight spacing between characters. For example, the text shown in the lower left-hand-side of Figure 14 is the MIKS.FNT for the alphabets. In Figure 8, the numeric and symbol characters are the MIK Goudy – Stick.FNT. New font sets are being developed and routinely added to the font library of the CAD program. At present, the above two font sets are fast to machine and present the best clarity for fine text.

4.2.5 Machining small “axisymmetric” parts

The Rotary Axis was recently developed as an add-on attachment to the JMCs. It was designed for cutting pipe, circular or radiused materials, and other “axisymmetric” features on round stocks.⁵ Tests were conducted to machine miniature interlocking features on 6.35 mm OD copper and stainless steel tubes. Figure 15 illustrates the two interlocking pieces. The nozzle with the 0.18 mm/0.38 mm ID ratio was used to machine these parts. Also shown is a miniature model of the



Figure 16. Acrylic model of Space Needle, in Seattle, M $\approx$ 590

Space Needle in Figure 16. The addition of the Rotary Axis has expanded the capability of JMCs from 2D to 2+D machining, greatly enhancing their utility for micromachining.

5. Discussion

During the course of the investigation of applying AWJ and WJ for machining fine features often required by micromachining, three orifice/mixing tube ID ratios, 0.18 mm/0.38 mm (0.007”/0.015”), 0.13 mm/0.30 mm (0.005”/0.012”), and 0.13 mm/0.25 mm (0.005”/0.010”), were used with a SUBMINIJET nozzle (preproduction) to demonstrate their capability for micromachining. The operating pressure was set to 348 MPa (50 ksi) and 220-mesh garnet was used as the abrasives. It was discovered that the kerf width of the machined features is about the same as the ID of the mixing tube. The nozzle worked well with the 0.18 mm/0.38 mm ID ratio. Frequent nozzle clogging was encountered when the 0.13 mm/0.25 mm ID ratio was used. The vacuum generated by waterjets decreases with decreasing IDs of orifices. For very small nozzle ID ratios, due to a low vacuum level generated by the waterjet through the orifice and/or high flow resistance through the mixing tube, abrasives would not entrain successfully into the waterjet resulting in frequent clogging of the nozzle. The vacuum is the lowest during the start of the waterjet as the pressure gradually increases to reach its operating value. As a result, nozzle clogging often takes place during initial piercing when the vacuum level in the mixing chamber is the minimum. Under such a situation, an air ejector could be used to boost the vacuum level inside the



Figure 14. MIKS stick font set on thin copper sheet, M $\approx$ 100

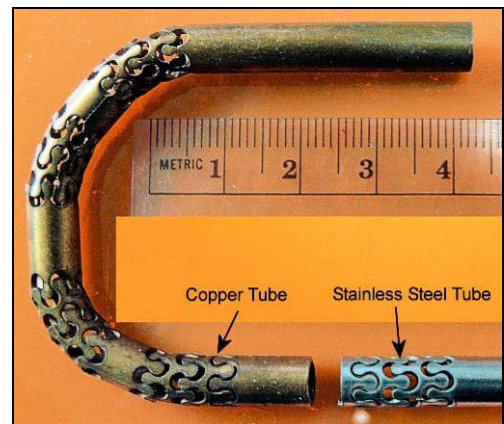


Figure 15. Interlocking features machined on metal tubes

⁵ <http://www.omax.com/omax.php?page=135>

mixing chamber and to clear wet abrasives accumulated inside the chamber, leading to clogging of the nozzle.

Based on the present results, the smaller kerf width achievable with the present AWJ setup is about 200 μm , consistent with the illustration in Figure 2. Further reduction in the kerf width would require reducing the ID ratio below 0.13 mm/0.25 mm, leading to considerable challenge in mitigating the problem of nozzle clogging. Although WJs could be employed to reduce the kerf width below 200 μm for relatively soft materials and thin metals, such as aluminum, the edge quality of WJ-machined features tend to be inferior to the AWJ-machined counterparts in terms of fraying and chipping.

In view of the great challenges described above, the author has been investigating alternate approaches for applying AWJs for micromachining. A proprietary process, stencil-aided waterjet stage (SAWS) as an attachment to the tip of the mixing tube, has been developed that would allow using existing AWJ nozzles for machining very thin slots. With the SAWS, clogging becomes less of an issue for micromachining with AWJs. Figure 17 illustrates two sets of slots machined with the SUBMINIJET nozzle with a 0.18 mm/0.38 mm ID ratio and a MAXJET[®] 5 nozzle together with the SAWS. The feasibility of machining slots with kerf width 100 μm or thinner has been demonstrated. Such high-aspect-ratio thin slots are very difficult to be machined with mechanical machining processes [2].

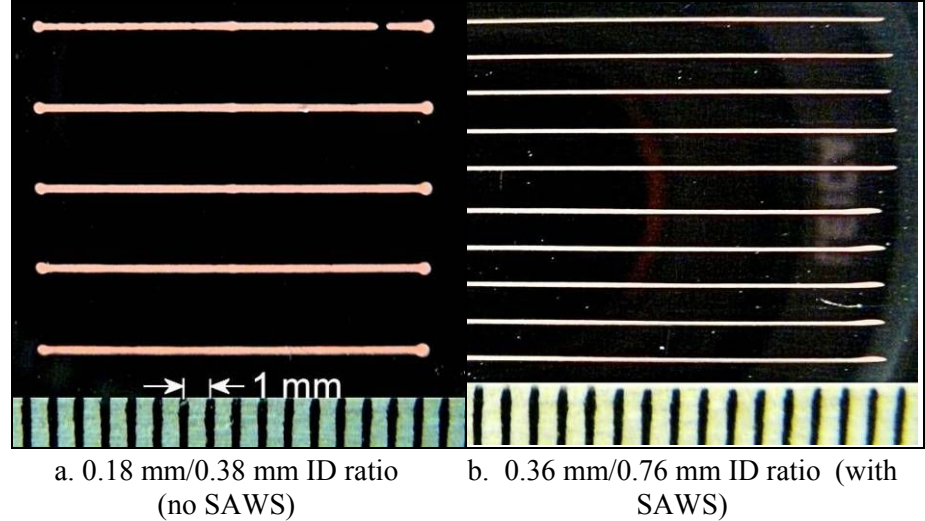


Figure 17. Slots machined with AWJs and novel AWJ/SAWS combination - 220-mesh garnet at 0.04 and 0.23 kg/min.⁶

Figure 18 illustrates micrographs of three sets of slots machined with AWJs (0.18 mm/0.38 mm and 0.13 mm/0.25 mm ID ratios) and with the AWJ (0.36 mm/0.76 mm ID ratio)/SAWS, respectively. Micrographs illustrated in Figure 18 corresponds to those narrow slots illustrated in Figures 17a, 10, and 17b, respectively. The superiority of the proprietary process to the conventional AWJ for machining micro slots with improved edge quality is evident. Without the use of the SAWS, the kerf widths achievable with AWJs are about the same as the mixing tube ID. The kerf widths vary slightly along the axis of the slots, particularly for those machined with the small ID ratio. When the use of the SAWS, the kerf width has been reduced to nearly $\frac{1}{4}$ of the mixing tube ID together with significant improvement in the edge quality. Another benefit of the SAWS is the ease of the need for further downsizing the nozzle and abrasives such that nozzle clogging would be minimized.

In an attempt to downsize the AWJ nozzle further for micromachining, considerable research has been conducted to understand and improve the gravity flow of extremely fine abrasives and to minimize nozzle clogging. As the nozzle ID reduces below 100 μm , the capillary effect plays an increasingly important role in the formation of micro AWJs. Attention has also been directed toward studying the flow through μAWJ nozzles - one of the most complex microfluidic phenomena that is supersonic and multi-phase with fluid-fluid, fluid-solid, and solid-solid interaction in a rapidly changing spatial environment. The above

⁶ SAWS is a proprietary waterjet micromachining process under development at OMAX Corporation.

effort has led to the development of novel processes that are promising in developing μ AWJ nozzles for micromachining. Most recently, experimental AWJ nozzles capable of machining parts that are about half the size of those shown in Figure 11b have been successfully designed, assembled, and tested. Figure 19 demonstrates recent achievement in further downsizing AWJ nozzles toward micromachining. Our goal is to develop μ AWJs capable of machining features around 50 to 100 μm .⁷

6. Summary

The advantages of waterjet technology described in Section 1 have prompted the investigation of applying the state-of-the-art and novel waterjet technology for micromachining. Laboratory tests were conducted to machine fine features with AWJs and WJs. Test results were examined to demonstrate their micromachining capability and limitation.

For AWJs, typical kerf width of machined features are about the same as the ID of the mixing tube or the beam diameter. For machining slots, the typical kerf width of slots is about 300 μm using an AWJ nozzle with a 0.18 mm/0.38 mm ID ratio. Kerf widths as narrow as 200 μm were achieved by using a nozzle with a 0.13 mm/0.25 mm ID ratio. The main limitation of downsizing the ID ratio is due to nozzle clogging as the vacuum created by the formation of the waterjet through the orifice decreases with the orifice ID. The jet pump effect becomes too weak to entrain abrasives through gravity feed. The use of an ejector has helped boost the vacuum inside the mixing chamber and reduce the frequency of clogging, but becomes ineffective as the ID ratio decreases further. For machining ribs, the

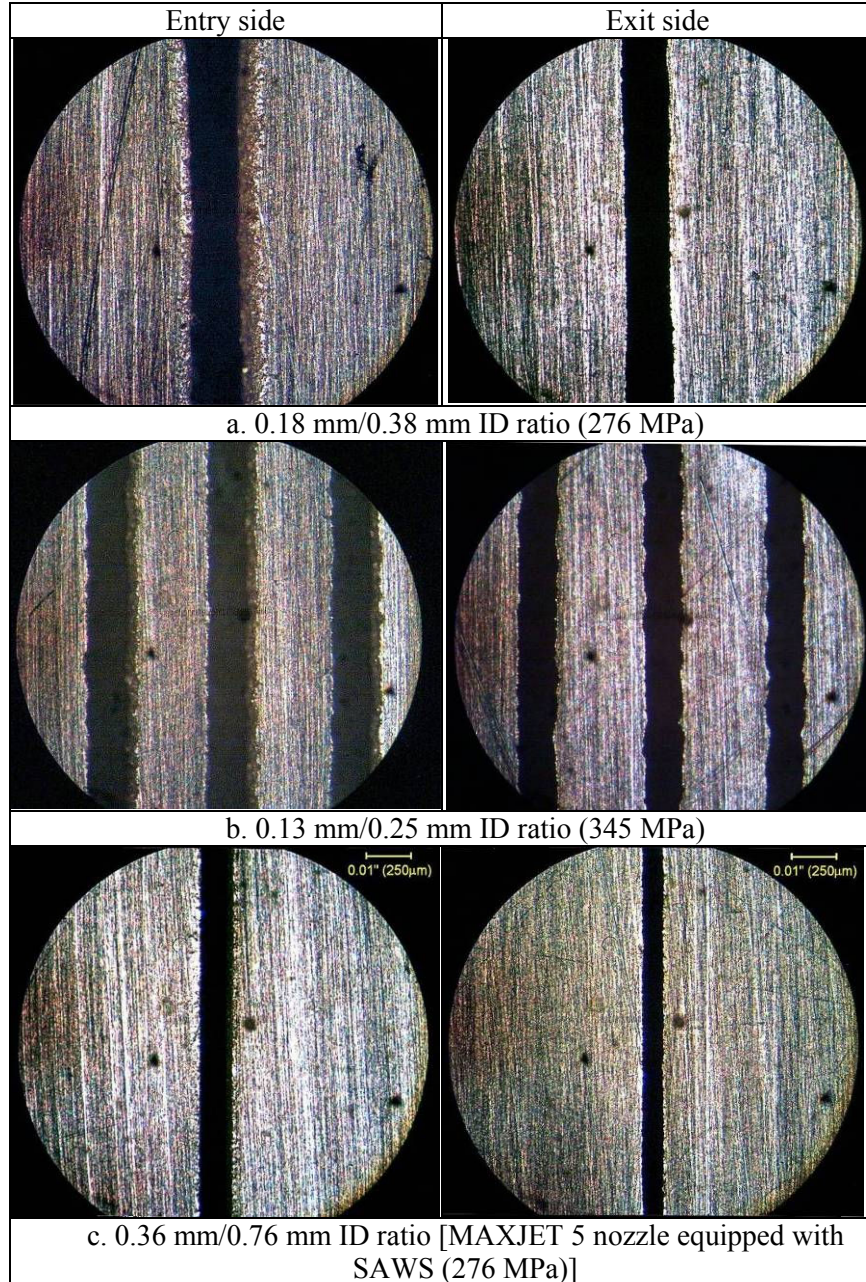


Figure 18. Micrographs of slots machined with conventional AWJs and AWJ/SAWS, respectively. Abrasives: 220-mesh garnet.

⁷ An NSF SBIR Phase I grant has been awarded to OMAX for demonstrating the feasibility of developing such a μ AWJ nozzle.

width could be quite small and is only limited by the stiffness of the parent material. For annotation, there are several font sets developed for both general machining and micromachining.

For relatively soft materials or thin soft metals, such as aluminum, waterjets could be used to machine slots with kerf width less than 100 μm . However, the quality of waterjet-cut edges is inferior to that of AWJ-cut counterparts. In the absence of abrasives, waterjets leave behind a considerable amount of frays that are difficult to remove.

As mentioned in Section 5, a novel and proprietary process was successfully developed to machine slots/slits 100 μm or finer. The SAWS enables machining micro features with superior edge quality that could not be otherwise achieved with conventional AWJs and WJs. Also, the SAWS process has eased the need for downsizing the nozzles. As such, nozzle clogging becomes less of an issue for waterjet micromachining. In a parallel effort, further downsizing of AWJ nozzles toward micromachining is being actively pursued. Our goal is to make available AWJ micromachine tools in anticipation of ramp-up demands for micro-machining when the micro-nano technology is mature for commercialization.

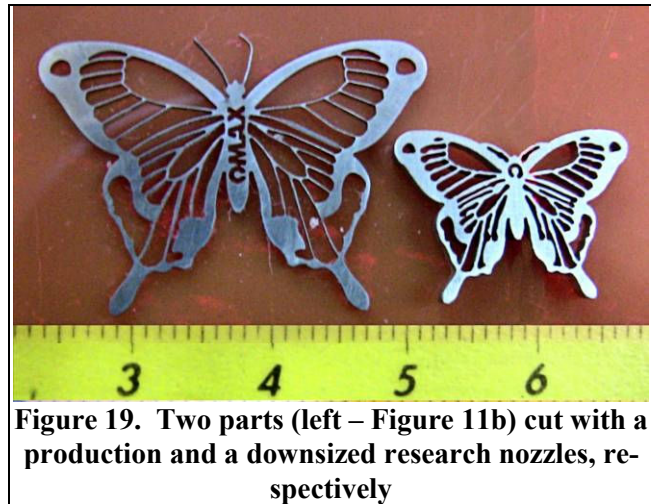


Figure 19. Two parts (left – Figure 11b) cut with a production and a downsized research nozzles, respectively

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