Precision machining of advanced materials with waterjets

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Abstract. Recent advances in abrasive waterjet technology have elevated it to a state where it often competes on equal footing with lasers and EDM for precision machining. Under the support of a National Science Foundation SBIR Phase II grant, OMAX has developed and commercialized micro abrasive water technology that is incorporated into a MicroMAX® JetMachining® Center. Waterjet technology, combined both abrasive waterjet and micro abrasive waterjet technology, is capable of machining most materials from macro to micro scales for a wide range of part size and thickness. Waterjet technology has technological and manufacturing merits that cannot be matched by most existing tools. As a cold cutting tool that creates no heat-affected zone, for example, waterjet cuts much faster than wire EDM and laser when measures to minimize a heat-affected zone are taken into account. In addition, waterjet is material independent; it cuts materials that cannot be cut or are difficult to cut otherwise. The versatility of waterjet has also demonstrated machining simulated nanomaterials with large gradients of material properties from metal, nonmetal, to anything in between. This paper presents waterjet-machined samples made of a wide range of advanced materials from macro to micro scales.

1. Introduction
Waterjet technology has made significant advancements in the past decade. For many applications of precision machining, it is now often competing on equal footing with existing machine tools such as lasers and electro-discharge machining (EDM) [1]. In particular, waterjet has several technological and manufacturing merits that cannot be matched by most existing tools. A list of such merits is given elsewhere [2, 3]. For a number of applications, waterjet is advantageous over other tools in terms of fast cutting speed and turnaround, setup simplicity, material independence, and preservation of integrity of parent materials. For example, as waterjet is a cold cutting tool that creates no heat-affected zone (HAZ), waterjet does not induce heat damage to parts as lasers, EDM, and plasma cutting do. Figures 1a and 1b illustrate a pair of titanium tweezers and a miniature stainless steel butterfly cut with a CO₂ laser and waterjet. The CO₂ laser induced considerable heat damage to the parts as indicated by the presence of discoloring and slag, leading to part warpage and surface hardening [1, 3, 4]. Waterjet, on the other hand, induced no such damage on the parts and therefore preserved the structural and chemical integrity of the parent materials (Figures 1a and 1b). For the miniature butterfly with many narrow slots and thin webs, the heat generated by the laser simply melted the thin webs, which were then vaporized (Figure 1c). Again, waterjet did not induce any heat damage to the parts. Besides, waterjet

² Waterjet is often referred to either the waterjet-only-jet (WJ) or abrasive waterjet (AWJ) depending on the properties of the materials to be cut.
exerted a minimal side force to the part during cutting. As a result, it is capable of cutting very thin webs without distorting them.

Figure 1. Typical heat damage by CO₂ laser [3].

[Courtesy of Center for Bits and Atoms (CBA)]

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In order to minimize the HAZ, solid state lasers pulsed at high frequencies and wire EDM cut with multiple passes must be used. Such measures significantly reduce their cutting speeds. As a result, waterjet cuts much faster than lasers and EDM [3]. Also, waterjet is material independent; it cuts materials that cannot be cut with lasers (e.g., reflective materials) and EDM (nonconductive materials). The versatility of μAWJ has also demonstrated for machining simulated nanomaterials with large gradients of material properties from metal, nonmetal, to anything in between [3]. Even for extreme precision parts, the versatile waterjet has been proven to be a preferred near-net shaping tool. Particularly for materials that are difficult to cut with other tools, waterjet net shaping would remove most of the bulk materials. The net-shaped part is readily to be finished by light trimming with a qualified precision tool. As such, the operating life of that tool is significantly extended [5].

AWJ is capable of 3D machining but must be carried out with discretion. One of the properties of the spent abrasives of AWJ, if not “tamed” or captured, still possess considerable residual cutting power that could induce damage to other parts of the workpiece and pose a potential hazard to the operators. In other words, AWJ is not inherently suitable for 3D machining by simply mounting the nozzle on a multi-axis manipulator. Because the simplest and most effective means to dissipate the residual energy of spent abrasives is to let the spent abrasives shoot generally downward into a column of still water, most AWJ systems are built on top of a water tank that also serves to support the traversing mechanism. Such AWJ systems that are operating within the limitations of safety are mainly designed for 2D machining [6]. Novel approaches have been developed to facilitate AWJ 3D machining while ensuring operation safety, by either manipulating the workpiece or incorporating accessories to the 2D
AWJ platform (Liu and Olsen, 2013). 3D sample parts cut with these processes are presented to demon-
strate the extended applications of 2D AWJ platforms for 3D machining.

Waterjet is amenable for micromachining as the nozzle can be downsized to generate jets with mi-
cron-size diameter [2, 7]. Supported by an NSF SBIR Phase II grant, OMAX Corporation developed
and commercialized micro abrasive waterjet (μAWJ) technology for meso-micro machining. The new
product was the MicroMAX JetMachining Center in which the μAWJ technology was incorporated. 3
With the addition of the MicroMAX, OMAX has established a full capability of precision machining
of most materials from macro to micro scales for a wide range of part sizes and thickness.

In this paper, the waterjet technology with emphasis on the μAWJ technology will be described
briefly. Detailed description of the technology is available elsewhere [8, 9]. 4 Examples of 2D and 3D
waterjet-machined parts that are made from advanced and delicate materials and with a wide range of
part size and thickness are presented to demonstrate the versatility of the technology. The potential of
waterjet for precision machining of various industrial and engineering components will be discussed
and demonstrated.

2. Objective
The main objective of this paper is to demonstrate the versatility of waterjet technology for machining
most materials from macro to micro scales for a wide range of part size and thickness. Demonstration
will be made by presenting a wide range of waterjet-cut examples. Performance comparison of water-
jet and other machine tools will be made when appropriate.

3. Technical approach and methods
Abrasive waterjet technology (AWJ) was commercialized in the late 1980s. Refer to a time line of the
technological development presented briefly by Liu [3]. At that time, in the absence of precision con-
trolling software and hardware, it was used merely as a rough cutting tool to take advantage of its ma-
terial independent property. Material removal is accomplished by eroding away the materials by either
the high-speed water of a water-only-nozzle (for relatively soft materials) or the abrasives (for hard
materials) that were accelerated by the high-speed waterjet (WJ) through the mixing tube. Such a
mode of material removal differs from other machine tools. It was perceived that there was considera-
ble potential for developing the technology into a precision machine tool provided the above merits
could be fully exploited. With such a vision, major efforts were devoted to advance the AWJ technol-
ogy in the past two decades. Advancement included but was not limited to development of a cutting
model for common engineering materials, position and cutting accuracies, control software and har-
dware, operational simplicity, cost effectiveness and fast turnaround, and material independence [2, 3].
The cutting model was developed based on extensive cutting of many materials. For each material,
unique indices of machineability and pierceability are uniquely defined [2]. These indices are used to
the cutting and piercing of various materials. The cutting model is one of the key parameters of the
PC-based CAD/CAM for automation, greatly enhanced the user friendliness of the technology for pre-
cision machining. There was no steep learning curve, unlike CNC tools, for new users to master the
operations of waterjet machining. New users could be trained in a week to learn how to design/cut
parts and perform system maintenance proficiently.

Under the support of an NSF SBIR Phase II grant, OMAX developed and commercialized μAWJ
technology for meso-micro machining [1]. The commercialized product was the MicroMAX JetMa-
chining Center, which was released for production in September 2013. With the addition of the Mi-
croMAX, OMAX has two product lines of JetMachining Centers capable of machining most materials
from macro to micro scales (the 5M advantage) with a wide range of part size and thickness.

As a premier manufacturer of waterjet equipment, OMAX invested heavily on R&D for product
improvement and demonstration for broadening applications of waterjet precision machining. In the

3 The MicroMAX (https://www.omax.com/omax-machine/micromax) has made the Finalist of the 2016 R&D 100 Awards.
4 www.waterjets.org
R&D and Demonstration laboratories, new processes are routinely being investigated for test cuttings of new materials and part geometries. For extremely precision parts, waterjet could serve beneficially as a near-net shaping tool. The near-net shaped parts could then be finished by light trimming them with appropriate precision tools. As such, the operating life of these tools are greatly extended.

A large portion of the test cutting was from requests by existing and prospective customers who were interested in how waterjet would benefit their operations. Other examples presented in this paper represent a collection of results of the test cutting on advanced materials using several JetMachining Centers equipped with various nozzles and accessories described in Section 4. Others are the results of collaboration between OMAX and its collaborating research institutes.

4. Facilities and equipment
At OMAX’s Headquarters, there are a R&D Laboratory and a Demonstration Laboratory equipped with several JetMachining Centers (JMCs). Figure 2 illustrates two JMCs – a MicroMAX and a Model 160X. In this section, waterjet nozzles together with the most common accessories are described for precision machining of 2D and 3D parts made from a wide range of materials from macro and micro scales.

![Figure 2. Two JetMachining Centers with different work envelops and accuracy.](image)

4.1. Nozzles
One of the unique advantages of waterjet is that it only needs one tool to qualify for multiple modes of machining - parting, drilling, turning, milling, facing, beveling. The single tool is the waterjet nozzle that has difference sizes to cover a wide range of part thickness. Typical nozzles include the Water-Only-Nozzle, MAXJET 5 nozzle, the MINIJET nozzle, and the 7/15 nozzle. Each nozzle can accommodate orifices and mixing tubes with different sizes of IDs. Figure 3 illustrates a schematic of the AWJ nozzle together with photographs of the four nozzles described above.

![Figure 3. AWJ nozzles.](image)

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5 7/15 nozzle refer to the AWJ nozzle with a 0.007” (0.18 mm) ID orifice and a 0.015” (0.38 mm) ID mixing tube.
4.2. Accessories
There are three popular accessories: (a) Tilt-A-Jet for taper compensation, (b) Rotary Axis for cutting axisymmetric features, and (c) A-Jet for beveling and countersinking. 3D parts with complex 3D geometry can be cut by combining the use of both the Rotary Axis and A-Jet. Figure 4 illustrates photographs of the Tilt-A-Jet, Rotary Axis, and A-Jet. 3D parts with complex geometry can be readily machined by combining the operations of the Rotary Axis and the A-Jet.

![Tilt-A-Jet and Rotary Axis and A-Jet](image)

**Figure 4.** Accessories.

Another useful accessory is the vacuum assist kit which is used during low-pressure piercing and cutting where the Venturi vacuum or the jet pump effect is too weak to entrain fully all the abrasive fed from the hopper. The kit was particularly designed for low-pressure piercing of delicate materials such as composites, laminates, and brittle materials such as glass particularly when miniature nozzles are used. Piercing damage often occurs when the tensile strength of the target materials is lower than the stagnating pressure developed inside the blind hole [2, 10, 11].

4.3. PC-based CAD/CAM
Waterjet machining is controlled by a PC-based Intelli-MAX Software Suite that is powerful while remaining intuitive and easy to use with no steep learning curve. From creating a drawing to importing part files with the PC-based CAD (LAYOUT), Intelli-MAX easily takes a design and prepares it with the PC-based CAM (MAKE) for machining. Cutting enhancements are achieved through the incorporation of a cutting model consisting of a lookup table by assigning machineability and pierceability indices to each common engineering material [2]. MAKE controls the traverse and several accessories to enable precision machining of 2D and 3D parts cost effectively with fast turnaround.

5. Results
5.1. Material independence
One of the technological merits of waterjet is its material independence as compared with other machine tools that are often material selective. Figure 5 illustrates photographs of AWJ-cut parts made from a wide range of materials that include metals, nonmetals, composites, laminates, and brittle materials. Such a versatility is superior of most other machine tools. For example, CO₂ lasers cannot cut reflective materials (e.g., copper) and EDM cannot cut nonconductive materials (e.g., PEEK and Lexan).
5.2. Performance comparison

The performances of several machine tools and the waterjet were discussed by Liu [3]. In this subsection, examples are given to compare the performances of waterjet, wire EDM, and solid state lasers, respectively. As illustrated in Figure 1, thermal damage to parts cut with CO$_2$ lasers and EDM is caused by the presence of the HAZ. Remedies to minimize the thermal damage is to slow down the cutting speed of wire EDM and to employ solid state lasers pulsed at high frequencies. As a result, the cutting speed of waterjet is considerably fast than those of solid state lasers and wire EDM when thermal damage by the presence of the HAZ must be minimized to preserve the structural and chemical integrity of parent materials. Figure 6 illustrates photographs of two tweezers cut with the AWJ equipped with a 7/15 nozzle and a wire EDM with a 0.15-mm-diameter wire. It took 38 min and 32 sec for the EDM and AWJ to cut the parts; the ratio of the cutting time is 70. 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 as can be seen from Figure 6. The tweezers were also cut with a solid state laser pulsed at 5 kHz to minimize the thermal damage to the part. Figure 7 shows photographs of the AWJ- and laser-cut tweezers. There was still a faint trace of discoloring was observed on the laser-cut tweezers. The cutting accuracy of the laser is considerably better than that of the AWJ as the laser has a spot size of 50 μm that is 5 times smaller than the 250 μm diameter of the AWJ. However, the AWJ cut over 200 times faster than the laser as the times to cut the part were 45 s and nearly 3 h, respectively.

Figure 6. AWJ- and wire EDM-cut titanium tweezers [3] (courtesy of MIT CBA).

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The solid state laser was also used to cut the miniature butterfly shown in Figure 1, as illustrated in Figure 8. The thickness of the part reduced from 0.5 mm to 0.25 mm. The cutting times for the AWJ and the laser were 2.2 min and about 60 min, respectively, a ratio of cutting time of 30. Again, the cutting accuracy of the laser is considerably better than the AWJ due to the fine spot size of the laser. No attempt was made to cut the butterfly with the wire EDM; its geometry is so complex with many piercings and internal features that it would be very difficult and time consuming to cut with the wire EDM.

5.3. Wide range of part size and thickness

The addition of the MicroMAX to the two product lines of OMAX’s JetMachining Centers has established a full capability of machining most materials from macro to micro scales. In practice, waterjet has been successfully machining aluminum blocks 200 mm and thicker. With taper compensation, Figure 9 illustrates several AWJ-cut aluminum blocks with nearly taper free edges. On the other hand, the μWJ technology has made considerable progress toward micromachining. Figure 10 illustrates a set of stainless steel and titanium tweezers to demonstrate the recent trend of the above progress in recent years.
5.4. Parametric shape generator

One of the built-in parametric shape generators available in the Intelli-MAX software suite is a “Gear, Rack, and Sprocket Shape Generator” for designing tool paths of those components. For example, the tool path of a gear can be readily generated by inputting the following five parameters: number of teeth, pitch, root fillet radius, pressure angle, and tip fillet radius. Waterjet was used to repair a damage segment of bisalloy wind turbine gear segment (100 mm thick and around 1.5 m in diameter), as illustrated in Figure 11. On the other hand, Figure 12 illustrates a set of miniature titanium planetary gears machined with the 5/10 micro nozzle. The components were nested on a titanium sheet (right). Tiny tabs were used to hold on the components that could be retrieved by breaking the tabs. The as-cut components were assembled into an operating planetary gear that was driven by a micro motor.

5.5. Machining delicate materials

For cutting internal features, the first step is to drill a starting hole. AWJ if untamed would build up large stagnating pressure inside the blind hole before breakthrough takes place. Delicate materials such as campsites, laminates, and brittle materials with weak tensile strength, the buildup of stagnating
pressure inside the hole would cause piercing damage provided the stagnating presses exceeds the tensile strength of the material [11, 13, 14]. Figure 13 illustrates typical AWJ piercing damage in terms of cracking/chipping (left) and delamination (right) for laminated glass and GX1 composite.

![Top view (28 mm x 28 mm)](image1)

![Edge view (0.5 mm and 1 mm)](image2)

a. Laminated glass  b. GX1 composite

**Figure 13.** Typical AWJ piercing damage.

Several remedies were developed by the author and his colleagues to minimize and/or mitigate AWJ piercing damage. Abrasive cryogenic jet (ACJ) using liquefied nitrogen as the working fluid was first developed [15]. Subsequently, a super-heated abrasive waterjet (FAWJ) was developed [10]. The working fluids of both the ACJ and the super-heated FAWJ evaporated as the jets exiting the mixing tube. Only a small percentage of the working fluids enters the blind hole, resulting in considerable reduction in the stagnating pressure. Both the jets succeeded in minimizing/mitigating the piercing damage. Figure 14 illustrates photographs of FAWJ-cut samples that are free of piercing damage.

![Top view (28 mm x 28 mm)](image3)

![Edge view (0.5 mm and 1 mm thick)](image4)

a. Laminated glass  b. GX3 composite

**Figure 14.** Mitigation of piercing damage with FAWJ.

The ACJ and FAWJ, however, were merely research tools that were too complex and not reliable for industrial deployment. Based on the concept of these tools, reliable Turbo Piercer and Mini Piercer were developed for drilling large and small holes, respectively. Figure 15 illustrates two samples cut with the Turbo and Min Piercers on an aerospace aluminum laminate (BAC1534-63F), respectively [2]. The laminate consisted of 19 layers of 0.076-mm-thick aluminum shims. The bonding strength of the adhesive between shims was relatively weak. It is imperative that stagnating pressure induced inside the blind hole must be lower than the adhesive strength to avoid delamination.
Figure 15. Samples of internal features cut with the turbo and mini piercers on aluminum laminate.

Carbon fiber is another material that was difficult to cut with conventional AWJ. By using the vacuum assist kit, low-pressure cutting at pressures as low as 35 MPa was used successfully to pierce this material without damage. Figure 16 illustrates photographs of a carbon fiber sheet and tube with internal features machined with the AWJ. The Rotary Axis was used to cut the internal features on the tube wall. A sacrificial carbide rod was placed inside the tube to protect the opposite wall of the tube from damaging by the spent abrasives.

Figure 16. Internal features cut on carbon fiber sheet/tube.

5.6. Machining difficult materials
The machineabilities of stainless steel, Inconel, and titanium are 80.8, 83.6, and 108, respectively [2]. In other words, waterjet cuts Inconel and titanium 3% and 34% faster than cutting stainless steel. Such a trend is opposite to machining these “difficult” materials with conventional tools such as CNC hard tools and EDM. As a result, waterjet are often used to machine these difficult materials. Even for extremely precise part, waterjet can be advantageously used as the near-net shaping tool. The net-shaped part can then be precisely trimmed with qualified tools. The operational life of these tools is greatly extended since the bulk of the material is removed by the waterjet.

Heat treatment are common practice to improve the performance of steel parts. For example, tool steel is often hardened by heat treatment to increase the Rockwell hardness from RC20 to as high as RC65. The hardened tool steel, however, is very difficult to machine with CNC tools. Steel parts are usually machined in its annealed state (RC20) and then are heat treated to the required Rockwell hardness. Unfortunately, the heat treatment brought above distortion of the finished parts that would degrade its tolerance. For waterjet, the machineabilities of annealed steel with RC20 and hardened steel with RC60 are 70.2 and 54.1, respectively. In other words, waterjet is capable of machining the hardened steel simply by slowing down the cutting speed by 77%. There is considerable benefit by ma-
chining the steel in its hardened state as the degradation of the part tolerance due to post heat treatment is mitigated.

For industrial applications, OMAX recently collaborated with Competitive Engineering to cut narrow slots on a 2.1 mm thick 440C stainless steel plate hardened to RC 58, as illustrated in Figure 17. The pockets and patterns were precut on the blank before waterjet machining. The current method to machine the part is by wire EDM. The EDM process requires three passes to cut each slot in order to minimize the HAZ. As a result, it takes over 6 hours to cut the part. By comparison, the MicroMAX using the 5/10 nozzle cuts the same features, to almost the same quality without the HAZ in only 23 minutes. In other words, the cutting speed of waterjet is better than 15 times faster than that of the wire EDM.

![Figure 17. μAWJ-machined slot patterns on a bonding extender for lapping thin-film ceramic substrates – courtesy of competitive engineering.](image)

For biomedical applications, titanium has been used extensively for fabricating orthopedic implants and prosthetic components. With the μAWJ technology commercialized, waterjet has been potentially applied to fabricate many orthopedic and prosthetic components [16]. For example, the titanium mesh cage shown in Figure 18c is machined with the μAWJ 5/10 nozzle on the Rotary Axis.

### 5.7. 3D parts

In order to take advantage of the 3D capability of AWJ while operating the machine within the limitation of safety [6], accessories were developed enable 3D machining using a 2D AWJ platform. The Rotary Axis as illustrated in Figure 4b was designed to machine many axisymmetric and 3D features on tubes, pipes, and other cylindrical parts. The A-Jet provided two tilt angles – one perpendicular to the X axis and the other perpendicular to the Y axis. The two tilt axes were controlled to a specific limited distance so that the abrasive waterjet stream is always shooting in a generally downward direction toward a machine’s water tank.

The A-Jet articulating head, for instance, tilts at any angle within its “120-degree cone of safety.” By combining the Rotary Axis and the A-Jet, 3D parts with complex geometry can be readily fabricated [17]. Figure 18 illustrates several 3D parts cut with the Rotary Axis and/or the A-Jet. Figure 18a illustrates the setup for cutting a slotted copper tube that serves as the stator/rotor of a novel low-resistance slot-less armatures for a high-efficiency motor/generator [18]. The Rotary Axis was rotating while cutting slots that are not parallel to the axis of the tube enabling the curvature of the slots conformed to that of the tube. Figure 18b is a photograph of the pair of stator and rotor. The width of the slots was around 0.300 mm. The μAWJ is the only tool that can be used cost effectively to machine the slotted copper tubes since lasers cannot cut copper because of its high index of refraction and the nonsymmetrical patterns of the slots present considerable challenge to EDM. Figure 18c presents addi-
tional photographs of parts cutting from various materials. The Rotary Axis was used to cut most of them except the “fish mouth” weld joint where its nonaxisymmetric geometry required the pairing the Rotary Axis and the A-Jet.

Figure 18. 3D parts with complex geometry.

5.8. Taper free parts

For certain precision parts, such as mechanical flexures, it is imperative that the edges be taper free for optimum performance. Figure 19 illustrates a monolithic aluminum flexure with six narrow flexural hinges 0.25 mm wide in plane (MIT patent pending). This part, which cannot be fabricated with CNC machining, laser, or EDM, serves as a part of a novel laparoscopic trocar and blade retraction mechanism to mitigate damage to internal organs caused by over puncturing [19]. Another application is for fabricating nonlinear load cells which were designed to be highly sensitive (1% changes in the force) with a large force range (five orders of magnitude). Figure 20 illustrates two such load cells, one with large-aspect-ratio flexures of constant width of 1 mm and the other with tapered flexures. The large-aspect-ration flexures were over 100 mm long. The waterjet exerts a minimum side force onto the workpiece and is most suitable for machining narrow webs with large aspect ratios [1]. Laboratory tests were conducted to demonstrate successfully that the performance of the load cell agreed well with the theory [20].
5.9. R&D at educational institutes

The user friendliness and the 5M advantage of waterjet technology have attracted the attention of educational institutes. For example, MIT has installed more than 15 JetMachining Centers including a MicroMAX on its campus. The Hobby Shop at MIT offers training classes for students, faculty members and alumnae. Trained users have used the machine for R&D, hobby projects, and prototyping. As a result, the JetMachining Centers have been the most used machine tool on campus. In particular, graduate students used the MicroMAX to build models and prototypes for their extracurricular activities and academic work. For example, the MicroMAX was used to machine 1-mm-thick electrically isolated alumina (Al₂O₃) clamping rings for a deep reactive ion etcher of silicon wafer. The µAWJ-cut ring and the setup of a deep reactive ion etcher are illustrated in Figures 21a and 21b, respectively.

OMAX offers considerable discount of its products to educational institutes for education purpose. This serves as an effective means to raise the awareness of waterjet technology.
Meanwhile OMAX has collaborated with MIT extensively to apply waterjet for various R&D projects. Selected projects are presented in Figures 1, 6-8, and 18-20, respectively.

5.10. Nanomaterials
One of the advantages of nanotechnology is its capability of manufacturing nanomaterials with large gradients of material properties from metal, nonmetal, and anything in between. Such nanomaterials would present considerable challenge to conventional tools because of their material selective limitation. At present, there are no commercial nanomaterials available. Simulated nanomaterials consisting of stacks of several thin sheets with different material properties were assembled. These stacks were then machined with the μAWJ to demonstrate the versatility of waterjet technology, as illustrated in Figure 22. The model consisted of a stack of eight materials: titanium, float glass, G10 composite, aluminum, Polycarbonate, stainless steel, carbon fiber, to copper. Few tools, if any, would be capable of cutting such a stack effectively.

6. Conclusions
The versatile waterjet technology has inherent technological and manufacturing merits that are unmatched by most existing machine tools. With the commercialization of μAWJ technology supported under the support of an NSF SBIR Phase II/IIB grant, waterjet has achieved the full capacity of machining most materials from macro to micro scales for a wide range of part size and thickness. Among the merits, waterjet requires only a single tool to qualify it for multiple machining modes from parting, drilling, turning, milling, facing, to beveling. Waterjet removes materials through erosion by either the high-speed waterjet or abrasives depending on the property of the workpiece. Such a material removal mechanism is the reason that waterjet is a material independent and cold cutting process. It also facilitates cutting advanced materials that are difficult or even impossible to cut otherwise. For each materi-
al, indices of machineability and pierceability are defined in the cutting model; these indices are one of the key parameters for automating the waterjet machining process.

In this paper, a collection of 2D and 3D samples cut with waterjet from various advanced materials for a wide range of part size and thickness is presented. The merits of cold cutting and low side force exertion to the workpiece enable waterjet to cut certain part geometries, such as large-aspect-ratio slots separated by thin webs that are too difficult to cut otherwise. This capability is most suitable for machining micro fluid channels used in heat exchangers, reactors, and reformers for energy production and storage [21]. As a cold cutting machine tool that does not induce the HAZ, waterjet cuts much faster than solid state lasers and wire EDM (up to 2 orders) as lasers must be pulsed at high frequencies and the wire EDM must cut multiple times to minimize the HAZ.

The versatility of waterjet was further demonstrated by machining delicate (composites, laminated, and brittle materials such as glass and silicon wafer) and difficult materials (alloys and hardened steel). Novel processes were developed to mitigate piercing damage to delicate materials based on the results of considerable R&D effort in understanding mechanism of AWJ piercing. Machining hardened steel helps mitigate part tolerance degradation resulted from the post heat treatment process. One of the highlights of the paper is to demonstrate cutting with the μAWJ nozzle a simulated nanomaterial with large gradients of material properties from metal, nonmetal, to anything in between. The simulated nanomaterials was assembled by stacking eight sheets of different materials - from titanium, float glass, G10 composite, aluminum, Polycarbonate, stainless steel, carbon fiber, to copper. As such, waterjet would serve as a preferred machine tool for cost-effective machining of nanomaterials when they are ready for commercialization.

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