

## APPLICATIONS OF ABRASIVE-FLUIDJETS FOR PRECISION MACHINING OF COMPOSITES

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### ABSTRACT

Abrasive-waterjets (AWJs) have been established as a cost-effective and material-independent tool for machining composites so long as no internal piercing/cutting is involved. During the initial piercing stage before breakthrough, a relatively large buildup near the bottom of the blind holes of static pressure occurs as high-speed water droplets decelerate, stop, and reverse their course. Damage such as delamination, cracking, and/or chipping results in composites with low tensile strength. Remedies using pressure ramping and vacuum assist techniques have shown limited success in mitigating piercing damage. An alternate remedy is to pre-drill holes with an attached drill head and then follows by AWJ cutting to minimize piercing damage. Advanced composites such as silicone carbide ceramic matrix composites (SIC CMCs) are difficult to machine with most machine tools. Silicone carbide fibers embedded in the CMC are known to be hard on contact tools. The ceramic matrix, on the other hand, does not have adequate tensile strength to resist damage during AWJ piercing/machining. A novel flash AWJ (FAWJ) which superheated the high-pressure water was successfully developed to preserve the structural integrity of delicate materials. Considerable efforts are being made to downsize AWJ nozzle toward micromachining of composites for applications in microelectronics, MEMS, bioengineering, and nanotechnology.

### 1. INTRODUCTION

The demand for composites in aerospace and industrial applications has been skyrocketing in the past decade and the same trend will continue for the next two decades. With commercial aerospace and wind energy (turbine blades) being the leading drivers and microelectronics not far behind, the composites industry has seen strong double-digit growth [1,2]. In particular, there has been a paradigm shift in aircraft design at Boeing and Airbus, with composites now specified for primary structures. Therefore, all future wide-body airplanes shipped from both manufacturers are based on the new paradigm. Both Boeing and Airbus are projecting multibillion-dollar markets for new airplanes over the next 20 years, particularly in Asia. In order to develop lighter, more efficient and more durable planes, Airbus is increasingly applying engineered composite material to aircraft designs. The airframe of the new A350 XWB (“Xtra Wide Body”) aircraft is more than 50 percent composite materials by weight [3]. The composites market segment, with aerospace as the primary driver, is looking at a growth rate of 19 percent compound annual growth rate (CAGR).

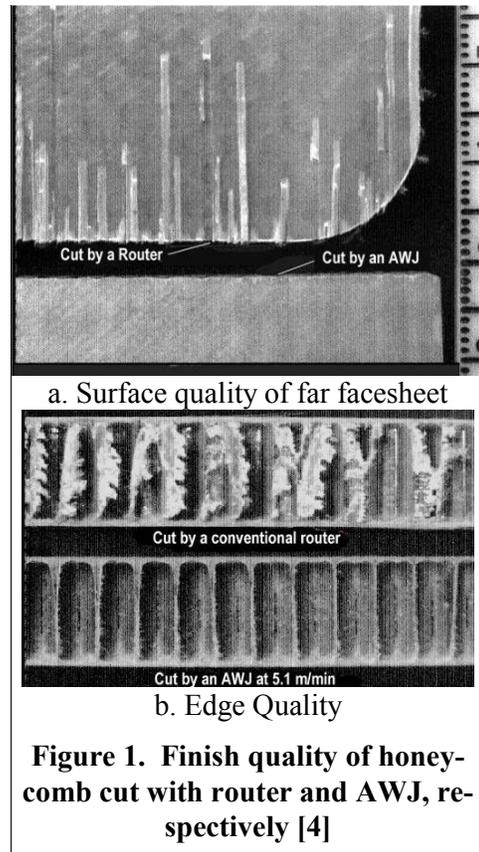
Conventional machine tools are often not suitable for machining composites. As shown in Figure 1, mechanical routers induce considerable tear and fray on nonmetallic honeycomb materials. Although advances in machine tool technology are developing in a rapid pace, it is no secret that machining composites has its challenges. When seeking alternatives to traditional machining, initial thoughts probably turn to laser, EDM, ion beam/electron beam cut-

ting and microwave cutting. All of them have certain advantages as well as drawbacks. For example, because carbon fiber requires high heat to cut, it is easy to introduce a heat-affected zone next to the cut when using laser. EDM struggles with certain materials exhibiting poor conductivity, such as fiberglass and ceramic matrix composites, while ion beam, electron beam and microwave are typically limited to cutting thin material, and are incapable of cutting contoured surfaces with tight tolerances. With the ever increasing usage of composites for aerospace and industrial applications, there is considerable demand for an alternate machine tool that is non-damaging, cost-effective, versatile, and environmentally and user friendly for machining a variety of composites.

There has been a global focus in developing nanotechnology that is expected to mature for commercialization in five to ten years. Nanoproducts will be built with nanomaterials that integrate seamlessly a number of materials at the molecular level. Nanomaterials would be considerably stronger and tougher than composites as the properties of nanomaterial could change continuously through its cross-section from conductive to nonconductive and/or from nonreflective to reflective with sharp gradients. As such, machining nanomaterials would present tremendous challenge to established machine tools because of the unconventional material properties.

The emerging waterjet technology has the potential to be a versatile machine tool for all materials - metals, nonmetals, composites and nanomaterials. In particular, abrasive-waterjets (AWJs) by entraining abrasives into an ultrahigh-pressure waterjet are presented in this paper for precision and/or net-shaping machining of composites. For machining a variety of composites without internal piercing, AWJs have been used widely for machining composites for aerospace and industrial applications [5,6]. AWJs have several inherent merits that are unmatched by most other machine tools:

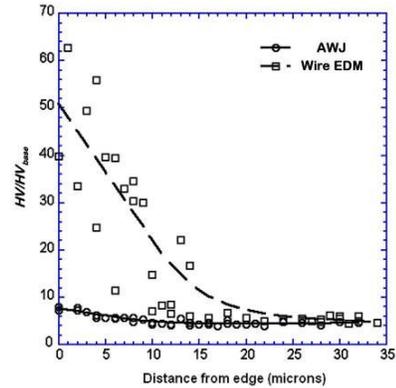
- Preservation of structural/chemical integrity – No HAZ and minimum surface hardening and no tearing with minimum fraying (see Figures 1 and 2)
- Fatigue performance enhancement by combining AWJ and low-cost dry-grit blasting [7,8,9]
- Material independence – Even for nanomaterials that are integrated seamlessly at the molecular level.
- No contact tool to wear and break when machining extremely hard and tough materials – For example, silicone carbide ceramic matrix composites
- Cost-effective with fast turnaround (no tooling or mask needed) for ones and twos (R&D) and/or for thousands (production) – Complete a part from design to finish in minutes to several hours, saving manufacturing jobs from outsourcing
- Minimum limitation in part size – from macro to micro



**Figure 1. Finish quality of honeycomb cut with router and AWJ, respectively [4]**

- User-friendly – PC-based CAD/CAM software for 2D, pseudo 3D, and 3D machining
- Compatible with just-in-time practice
- Multi-mode machining – Single setup for roughing, parting, drilling, turning, milling, and grooving
- Amenable to machining high-aspect-ratio ribs/slots – minimum force asserted onto work pieces
- Maximize use of materials to minimum waste – stacking together with nesting software [10]

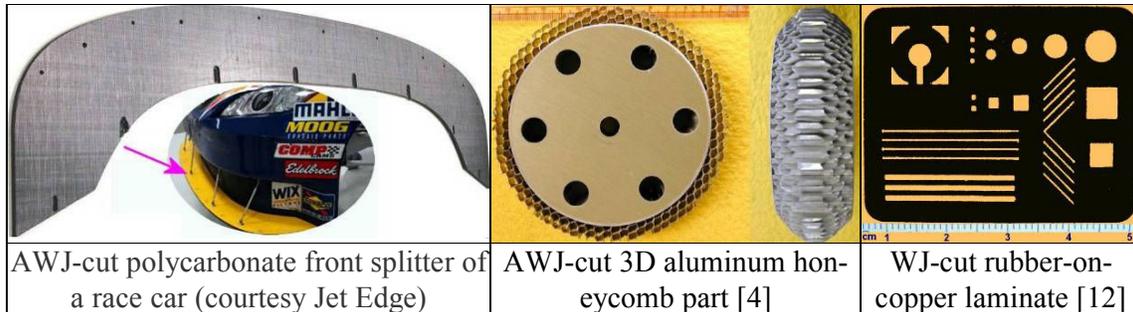
Figure 2 compares the surface hardness measured on titanium edges cut with AWJ and EDM (rough cut) processes. The induced hardness normalized by that of the parent material cut by the AWJ is five times higher than that cut by EDM. The thickness of induced hardening is also larger for the EDM-cut edge than the AWJ-cut counterpart. Micrographs of the edge surface show a relatively thick recast layer on the EDM-cut edge (not shown here).



**Figure 2. AWJ and wire EDM induced surface hardness on titanium [10]**

The above features are most suitable for applying AWJs to machine almost any materials including composites [10]. For composites, AWJs have been used widely for external machining that does not require internal piercing such as cutting, beveling, trimming, parting, singulating, and patterning, etc. [11]. Figure 3 illustrates typical composite parts machined with AWJs/WJs.

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**Figure 3. Typical composite parts cut with AWJ/WJ**

When internal piercing is required, AWJs often induce damage to delicate materials such as composites, laminates, and extremely brittle materials that have weak tensile strength of either the composite or binder material. During the initial piercing stage before breakthrough, a large static pressure is built up as the high-speed water droplets decelerate, stop, and reverse their courses near the bottom of blind hole. This is simply a conversion of kinetic energy back into potential energy [13]. For those materials with tensile strength below the static pressure buildup inside the blind hole, damage such as delamination, cracking, and chipping would result.

Current remedies to minimize the above damage include pre-drilling a starting hole with a drill attachment to alleviate static pressure buildup inside blind holes or exercising pressure ramping to minimize pressure buildup while abrasives are being delivered to the target work piece during initial AWJ piercing. Both remedies have resulted in some success in minimizing damage induced by AWJs/WJs to relatively soft and thin delicate materials when internal

piercing is required. For hard and tough materials, particularly for large thickness, the above two remedies could run into difficulty. For example, when the aspect ratio of the starting hole is large, the drill may not be sufficiently stiff to pierce straight holes. For very tough and strong materials such as silicone carbide ceramic matrix composites (SiC CMCs), the drill head will experience considerable wear and would not last very long. In fact, SiC CMCs are notoriously known to be a frequent tool breaker. On the other hand, pressure ramping must be carefully calibrated and optimized for each and every material and geometry to minimize the piercing damage. In most cases, vacuum assist by attaching an external ejector is needed to help expedite the delivery of abrasives to the target material surface and to prevent nozzle clogging. In addition, vacuum assist must accompany with water flushing to clear the wet abrasives in the outlet of the vacuum assist [3]. As a result, a total of four ports must be machined on the AWJ nozzle in order to facilitate both vacuum assist and water flushing, making the nozzle very bulky and awkward to maneuver. A part of the abrasives is removed by the vacuum line rather than being used for cutting, resulting in high abrasive consumption. The externally activated vacuum assist also tends to interfere with the waterjet and reduces its efficiency in accelerating the abrasives. This in turn reduces the overall cutting efficiency of the AWJ.

For machining hygroscopic materials and other special applications, abrasive cryogenic jets (ACJ) using liquefied nitrogen ( $LN_2$ ) were developed [14]. It was discovered that the ACJ was capable of mitigating piercing damage in a variety of delicate materials. As a result of phase change of the  $LN_2$  upon exiting the orifice and mixing tube, most of the  $LN_2$  evaporate before entering into the blind hole. Static pressure buildup inside the blind hole is thus minimized. Therefore the structural integrity of the target material is preserved. The ACJ is however not an economically and engineering viable industrial tool because its bulkiness (huge cryogenic storage tank), hush to the components (ultrahigh-pressure at cryogenic temperatures), and potentially hazardous to the operators (ventilation issue). To capitalize on the benefit of the phase change of the working fluid, a novel flash AWJ or FAWJ was developed by superheating the high pressure water such that superheated water would change into steam upon exiting the orifice and mixing tube (patent pending) [15]. For piercing in delicate materials, the superiority of FAWJ over AWJ in preserving the structural integrity of composites has been demonstrated [16]. This paper further demonstrates the merits of FAWJ over AWJ for machining internal features in variety of composites. The success in developing the FAWJ has helped realize the full potential of waterjet technology as a material independent machine tool.

This paper presents the applications of AFJs for machining a variety of composites. Section 2 describes the operational principle of AFJs - AWJ and FAWJ, equipment, and setups. Section 3 present examples cut with the AWJ. In Section 4, comparison of the AWJ and the FAWJ for machining internal features is made to demonstrate the ability of the FAWJ in mitigating piercing damage in delicate materials not just limited to composites. A summary and a plan for future development are given in Section 5.

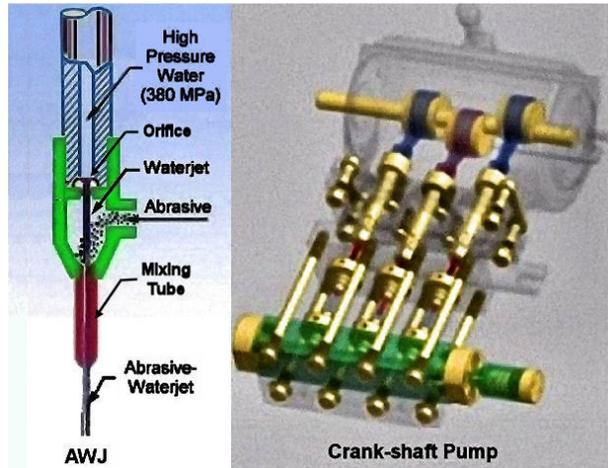
## 2. WATERJET TECHNOLOGY AND FACILITIES

### 2.1 *Waterjet Technology*

An ultrahigh-pressure (UHP) AFJ is formed by forcing a pressurized working fluid via a UHP pump up to 600 MPa (87,000 psi) through a small orifice. For illustration, Figure 4 shows drawings of an AWJ nozzle and a direct-drive crankshaft pump. 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.

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 4. UHP crankshaft pump and nozzle configurations**

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.

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 1970s. 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.

To create an FAWJ, resistive heating by applying low voltage and high current electric power from two welding power supplies was applied to four sets of 6.1-m long high-pressure tubes just upstream of the AWJ nozzle. Water entering the coil pack was superheated rapidly to exceed 100 deg C before exiting AWJ nozzle. The hardware components of the FAWJ are described in the next subsection.

## **2.2 Facilities and Key Components**

### **2.2.1 JetMachining Center with the FAWJ option**

Hole piercing tests were conducted by using one of OMAX's JMCs installed in the Engineering Laboratory. The JMC was a Model 2652.<sup>1</sup> It consists of four key elements: (1) a high-accuracy motion controller operating by a PC-based AWJ expert program; (2) a precision bridge X axis and Y cantilever axis rigidly mounted to the cutting table with a working envelope of 1.3 m x 0.7 m; (3) an AWJ delivery system which forces high-pressure water through a self-aligned nozzle consisting of a sapphire orifice (0.25-mm diameter) and a 6.5-cm long

<sup>1</sup> <http://www.omax.com/waterjet-cutting-machines/model-2626.php>

tungsten carbide mixing tube with an ID of 1.52 mm; and (4) a 30-KW crankshaft pump. Figure 5 illustrates a drawing of the Model 2656 with the FAWJ option. The basic Model 2656 includes all components except the two in red rectangles. The two FAWJ components in red rectangles are the high-pressure coil pack and the power supplies, respectively.

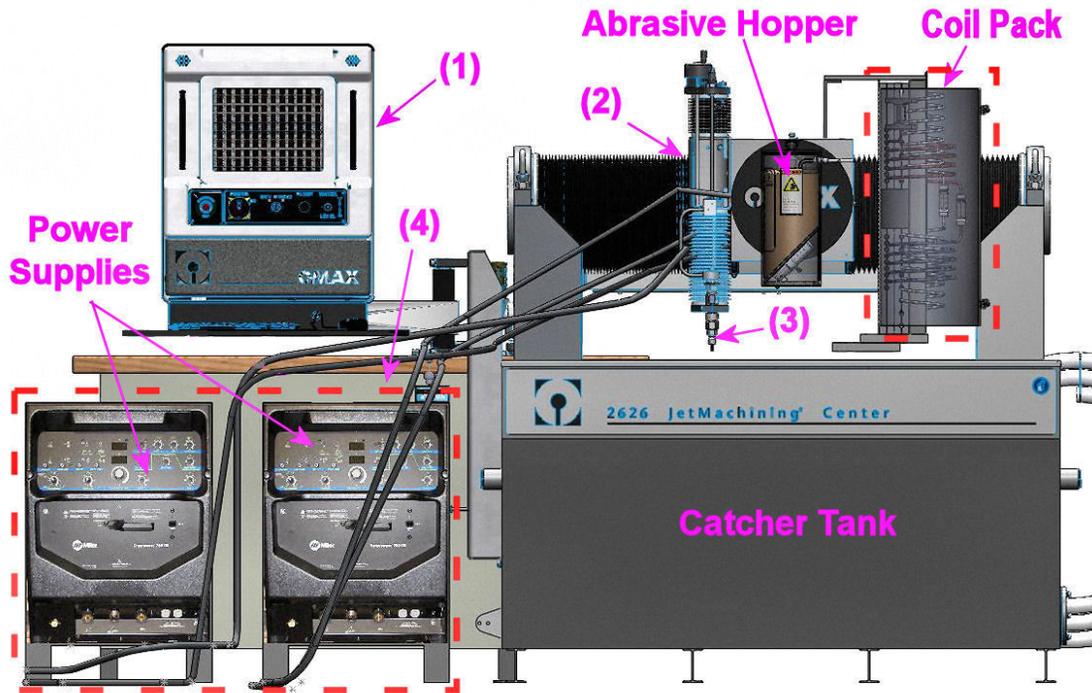


Figure 5. 2626 JetMachining Center with FAWJ option marked in rectangles of dashed edges in red

## 2.2.2 FAWJ prototype

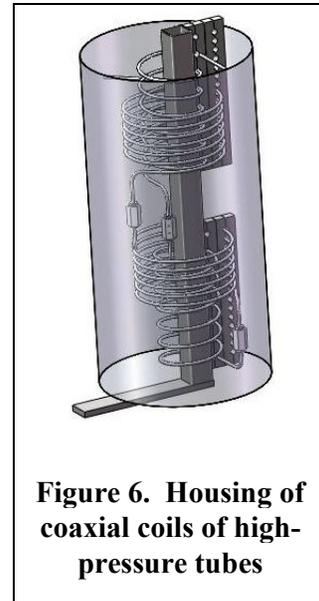
The FAWJ prototype includes the resistive heating subsystem, closed-loop control system, vacuum booster, abrasive control circuit and FAWJ nozzle assembly. The FAWJ prototype was mounted onto an OMAX JetMachining<sup>®</sup> Center for carrying out piercing and cutting tests. Figure 5 illustrates the over system assembly. Individual components of the FAWJ prototype are described below.

### 2.2.2.1 Resistive Heating Subsystem

**Power Supplies** - Based on preliminary testing and research, resistive heating was chosen as the best method to superheat the water used in the FAWJ system. For safety and efficiency reasons, a low voltage, high current power supply was chosen. We chose to use a commercially available unit with sufficient power to meet the requirements of heating a given quantity of water during the latent time it spends in the heating system. The power supplies were two Miller Syncrowave 250DX used for Stick/MIG/TIG welding.

**Superheating Module** - The superheating module consists of a high-pressure tube coil pack with four 11.5-ft (5.5 m) coils and connectors housed in a metal casing. Special couplers were developed to join all high-pressure tubes that were subject to thermal shock due to rapid temperature rise and drop. Figure 6 illustrates a version of the module.

**Controller** - During initial testing, we determined that a closed-loop system would be required to control the fluid temperature as well as to prevent the pressurized portion of the super heater from exceeding safe limits. The safe limit of the tubing was determined to be 700-800 degrees F. A multi channel PLC was selected to handle the control aspects of the super heater. The controlling inputs were to be the coil temperature and the FAWJ chamber pressure. The outputs were to be power level inputs to the super heater power supplies. Each of the two power supplies were individually controlled. The temperatures were all measured using type K thermocouples. The thermocouples in the tubing coils were in direct contact with the tubing wall and the chamber thermocouple was installed bare inside the chamber. The PLC was then programmed to maintain a preset temperature of the fluid entering the mixing chamber. Additionally, it had to accommodate various system initial temperatures.



#### 2.2.2.2 FAWJ Nozzle Assembly

**FAWJ Nozzle** - As described in Section 3.2.3, the FAWJ nozzle consisted of a 0.18 mm (0.007") ID diamond orifice and a 0.53 mm (0.021") ID mixing tube. The 3 to 1 diameter ratio was chosen to accommodate the large amount of hot steam as the superheated water changes phase upon exiting the orifice. A metal-to-metal seal was used between the nozzle body and the orifice mount onto which the orifice was formed. A diamond orifice was chosen as thermal shock quickly destroyed the sapphire orifices. There were two access holes on the nozzle body at the mixing chamber just downstream of the orifice, serving as the abrasive feed port and the vacuum booster port, respectively.

**Vacuum Booster** - A vacuum booster (VB) was fabricated by modifying a carbide sand blasting nozzle. The operating life of the carbide-based VB has significantly increased its operating life due to abrasive wear. Just downstream of the VB port, dripping water was supplied to the VB tube via a tee to wash away accumulations of wet abrasives along the VB tube and maintain a steady vacuum rate.

**Abrasive Hopper** - A standard abrasive hopper for the JMC was used. Two abrasive feed valve assemblies, each consisting of an air actuated on-off valve, were used for the FAWJ. The first assembly was for the low abrasive flow rate used during low pressure FAWJ piercing, and the second one was for the high abrasive flow rate used during cutting. The control circuit was controlled using OMAX pc-based CAM program MAKE's low pressure output signal. When in the low-pressure mode, one abrasive feed valve would be opened; when switching to high-pressure mode, a second valve would open. Unequal metering valves resulted in a very low piercing abrasive flow rate and a very high cutting abrasive flow rate that was ideal for the FAWJ application. 120-mesh garnet (HPX) was used for most of the piercing and cutting tests.

#### 2.2.2.3 Software Components

Two sets of software components were developed for operating the FAWJ. The first set controlled the PLC that operated the welder power supplies for superheating the water of the FAWJ. The second set was an add-on to MAKE that combined the piercing with the FAWJ under the flash mode and the subsequent cutting with the same nozzle, but operating in the

non-flash mode. The PLC was programmed in a simple ladder logic format to provide a closed-loop control of the heating circuit. The jet stream temperature and the individual coil temperatures were used to independently control the two power supplies. The upstream super heater circuit was setup to provide maximum power input during most of the operating cycle while the downstream circuit was set up as a “fine tune” heating element. The modification to MAKE was in the form of a bitstream editor. This editor allowed a standard MAKE cutting file to be modified by inputting the proper FAWJ controls into pierce points. The resulting system was easy to use once the proper timing parameters for a given material were determined.

### 3. AFJ-MACHINED COMPOSITE SAMPLES

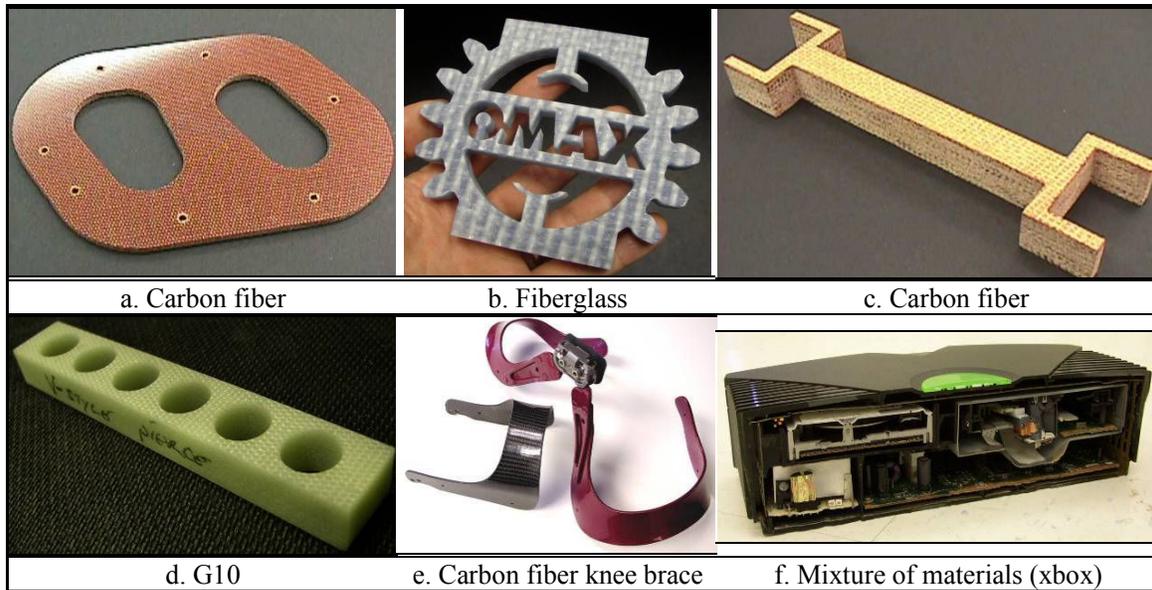
As discussed in previous sections, conventional AWJs have been successfully used for machining composite parts as long as there is no internal piercing involved. For machining external features, a variety of composite materials could be machined with AWJs to demonstrate their unique capability of material independence. On the other hand, AWJs are so powerful that, if not properly controlled or tamed, they could induce damage to composites with weak tensile strength of one of the composite components during initial piercing. Although there are remedies such as using an attached drill head or pressure ramping to prevent damage during initial piercing, they only work with limited success, as pointed out in Section 1. A novel superheated flash abrasive waterjet (FAWJ) was developed successfully as a low-cost and portable emulation of the ACJ to take advantage of the phase changing phenomenon for minimizing piercing damage [15, 16].

In this section, composite samples machined with AWJs and FAWJs are presented and compared to demonstrate the versatility and limitations of AWJs. When AWJs fail to machine internal features in delicate materials, FAWJs are available to fill in. First, AWJ-machined composite samples that do not require internal piercing are presented in Figures 7 and 8. Second, the damage induced by AWJs during initial piercing of delicate composites is illustrated in Figure 9a. Finally, the superior performance of the FAWJ is presented in Figure 9b.

#### 3.1 *Samples Machined with AWJs*

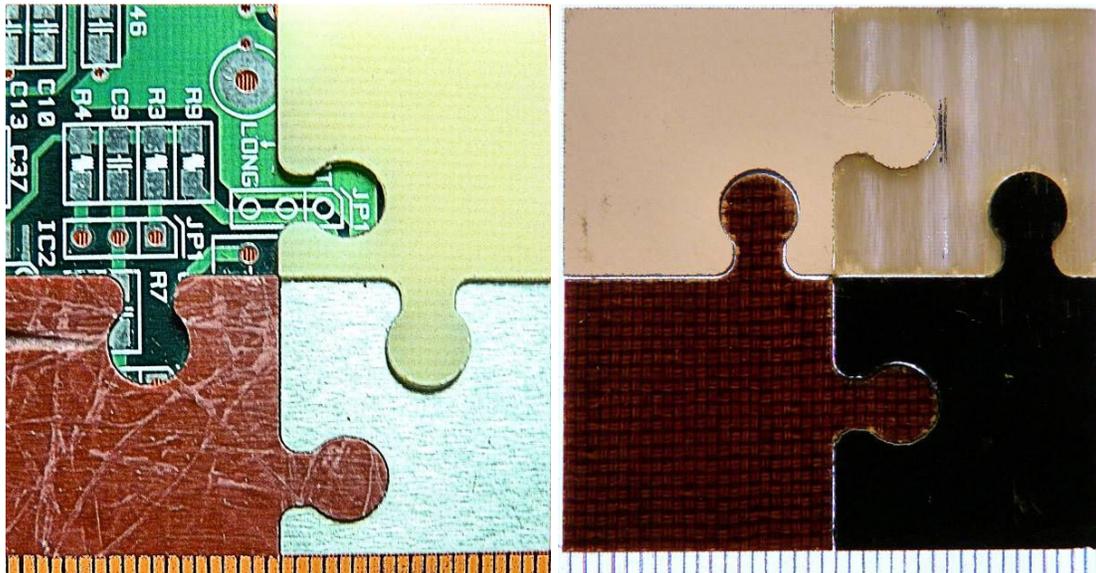
##### 3.1.1 **Cutting external features**

For patterns that do not require internal piercing, AWJ could be used cost effectively with fast turnaround to machine a variety of composites with no induced damage. Figure 7 illustrates several such composite parts machined with AWJs. For certain composites, lower the pressure from 345 MPa (50 ksi) to about 241 MPa (35 ksi) helps to reduce the degree of chipping on the edge of the jet exit surface. Holes of different sizes and/or various internal features were machined on the samples shown in Figures 7a, 7b, 7d and 7e. To avoid piercing damage that could potentially lead to delamination, cracking, and chipping, the option of low-pressure piercing was often chosen. For relatively large holes, minor damage is acceptable as damage area would be cut away. Note that the metal gear mechanism shown in Figure 7e was also machined with AWJs. Figure 7f is an AWJ-cut XBOX made from a handful of metal and nonmetal materials. It is an interesting way to demonstrate the advantages of waterjet technology for cutting most materials and for cutting thick structures. Because of the mixes in material and in component geometry, the XBOX might be difficult to cut with either a laser, EDM, or other established machine tools.



**Figure 7. Composite samples machined with AWJs**

Additional composite parts machined with AWJs are illustrated in Figure 8 where each puzzle piece was cut from a different composite or laminate. These pieces were cut by activating the Tilt-A-Jet that is controlled dynamically to cut square edges with negligibly small taper, leading to snug fit of all the puzzle pieces.<sup>2</sup> Again, a number of these materials could present a problem to established machine tools. For example, the circuit board would present difficulty to photochemical etching because of the vastly different etching rates of individual materials that are distributed irregularly on the board, particularly for multilayered circuitry boards.



**Figure 8. Composite puzzle samples machined with AWJs**

It should be emphasized that waterjet technology would be a favorable tool to machine nano-materials that integrate seamlessly several materials in the molecular level. As the interior properties of nanomaterials could vary continuously from conductive to nonconductive or from nonreflective to reflective such that a single material selective machine tool such as EDM or lasers would have difficulty to cut them.

### ***3.1.2 Cutting internal features***

For composites with relatively high tensile strength, AWJ piercing should be fine by simply lowering the piercing pressure. Once breakthrough takes place, high-pressure cutting could then resume. For relatively large internal features, small damage could be tolerated so long as its affected area is to be cut away. For composites with weak tensile strength, piercing even under low pressure together with pressure ramping and vacuum assist, is still insufficient to prevent from damaging the parts. Examples of piercing damage in various composites, laminates, and brittle materials have been demonstrated elsewhere [16]. Figure 9a illustrates several composite parts that were damaged by initial piercing with the AWJ even operating with pressure ramping and vacuum assist. The parts were cut into 2.8 cm x 2.8 cm square pieces. The thickness of the parts are shown in parentheses after the names of the material in the left-most column of the figure. For each part, the photos of the top, bottom, and side views are shown in three columns. For thin materials, a magnified side view is added in order to show the AWJ induced damage. There are multiple damage on the parts as they were cut with five internal piercings. As can be observed from these photos, the most common damage is cracking, delamination, and chipping. Delamination often results in considerable thickening of the part.

When pressure ramping together with vacuum assist fails to produce good results, predrilling holes at the locations where internal piercing is required are used as one of the remedies to mitigate AWJ-induced damage. Attaching a drill head to the AWJ systems is generally available as an option from OEM manufacturers.

### ***3.2 FAWJ-Machined Parts***

To demonstrate the ability of mitigating piercing damage by superheating the high-pressure water, the FAWJ was applied to machine the same composite parts shown in Figure 9a. Photos of the FAWJ-machined parts are illustrated in Figure 9b to facilitate a direct comparison of those illustrated in Figure 9a. It is evident from the comparison of the two sets of photos that the structural integrity of the FAWJ-machine composites is preserved. No part of the samples in Figure 9b shows any cracking, delamination, and chipping.

It is confirmed that the buildup of static pressure induced by AWJs inside blind holes is the primary cause for damage to delicate composites during the initial piercing before breakthrough. The phase change of the superheated water of the FAWJ and of the LN<sub>2</sub> of the ACJ upon exiting the nozzle minimizes the amount of working fluid in the liquid stage entering the blind hole. In the absence of liquid inside the blind hole, a large buildup of static pressure in the blind hole could not take place. As a result, target materials with weak tensile strength would survive without damage.

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<sup>2</sup> Tilt-A-Jet is a registered trademark of OMAX Corporation (<http://www.omax.com/accessories-tilt-a-jet.php>).

For the conventional AWJ, pressure ramping with vacuum assist is designed based on the same principle of reducing the buildup of large static pressure inside blind holes. It is essential that abrasives are delivered to the target surface as fast as the high-speed water. Damage would result immediately provided that the supply of abrasives is interrupted such that the jet is void of abrasives momentarily. Therefore maintaining a constant flow of abrasives is of the utmost importance when AWJs are applied to machine composites, particularly those with low tensile strength.

### 3.3 AWJ Micromachining

There is considerable demand for machining miniature mechanical components, microelectronics, microelectromechanical systems (MEMS), biomedical components, and nanoproducts that are made of various composites and nanomaterials. The inherent merits of waterjet technology described in previous sections have enabled AWJs to become one of the preferable machine tools for these applications. One of the challenges would be to downsize the AWJ nozzle to a size suitable for micromachining. Realizing the potential of waterjet technology, manufacturers of waterjet machine tools have made considerable investment in developing AWJ micromachining capability [11,17,18,19]. For example, the rubber-on-copper laminate (Figure 3c) and the puzzle pieces (Figure 8) were machined with a production miniature nozzle with a 0.18 mm (orifice ID)/0.38 mm (mixing tube ID) nozzle combination. Novel processes have been developed to operate this miniature nozzle without needing vacuum assist and water flushing, greatly reducing the overall nozzle dimensions and simplifying its control and maneuverability for machining. Research and development are being conducted to further downsize AWJ nozzles toward micromachining. At present, a 0.09 mm/0.21 mm ID ratio was successfully tested without the use of vacuum assist and/or water flushing. Figure 10 illustrates several miniature composite parts machined with this research nozzle. As we continue downsizing AWJ nozzles, smaller and smaller parts could be fabricated.

Figures 10a through 10c are photos of three miniature dragons machined from three composite materials: G-10, carbon epoxy, and fibreglass. The thickness of each material is shown in the captions. To view both the top surfaces and the edges of the parts, the photos were taken at a small inclined angle from the vertical. Figures 10d through 10f are photos of three miniature bikes. The materials are G-10, carbon epoxy, and carbon fiber, respectively. Figure 10g is a miniature key chain showing both the top surface and one of the edges. Figure 10h is the side view of Figure 10e; both the individual carbon fibers (black) and the epoxy layer (translucent) are distinguishable in these Figures. Figure 10i illustrates the photo of a penny and a “ $\mu$ ” symbol enclosed in a circle. The penny with a butterfly machined on it serves as a scale reference. When the photos of individual parts are zoomed to match their scales, the length of dragons is about the same as the penny’s OD whereas the length of the smallest bike equals to only one-half of that. Most importantly, the details of small features that are in the order of 100  $\mu\text{m}$  remain sharp and crisp. There is no delamination or chipping on the edges. The thickness of the wheel of the smallest bike is about 200  $\mu\text{m}$ .

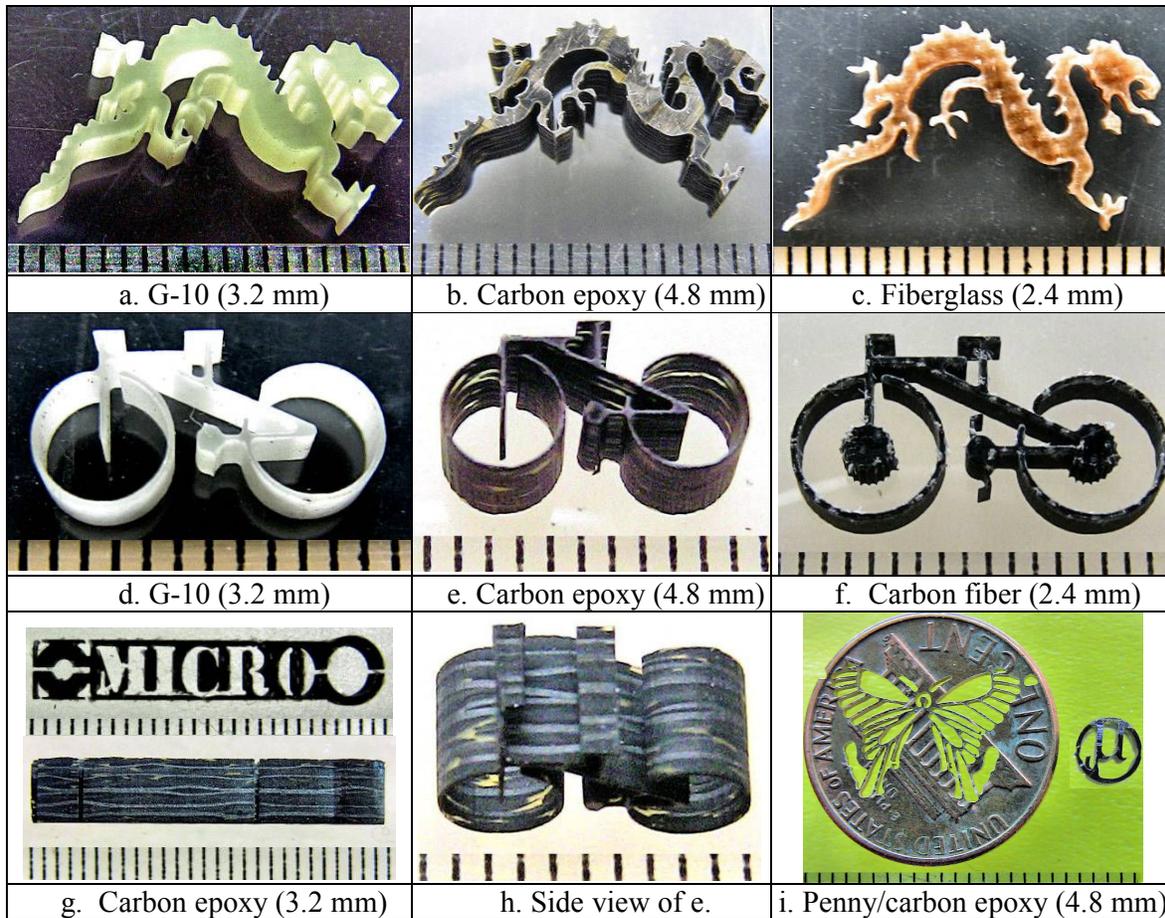
Abrasive-waterjets are most suitable for machining small features in these composites because of their inherent characteristics, namely being a cold cutting process and a material independent tool. It is well known that AWJs exert a very small force onto the work piece; the force is proportional to the beam diameter of the jets. First of all, it would be impossible to machine composites with EDM because they are nonconductive. Contact machine tools are out of the question for this application because of the large reactive force exerted on the work piece and poor edge quality. The heat generated by most lasers would tend to melt the thin

walls or webs of these parts. Femtosecond lasers could be used to alleviate the heat issue but are not cost effective for this application. Further, laminates and composites may pose a scenario where the laminate/composite is made up of two dissimilar materials whose fabrication methods are vastly different as well. Hard metal coated fibreglass is such an example. A hard metal normally requires EDM methods to shape while the fibreglass would respond best to hard tooling such as a burr or drilling operation to shape. Abrasive-waterjets bridge this gap with their multi-material cutting ability and are the perfect solution for exotic materials.

	a. AWJ with pressure ramping & vacuum assist			b. FAWJ		
G-9 Garolite (1.5)						
Carbon Epoxy Flat Panel (4.5)*						
Foam Plastic (12)						
Thermal Plastic Laminate (20)						
G-10 (10.8)						
G-10 (2.5)						
G-10 (2.1)						
Fiberglass (1.6)						
Laminated Glass (4.4)						
	Top	Bottom	Edge	Top	Bottom	Edge

\* Supplied by Boeing

Figure 9. Composite samples machined via AWJ with pressure ramping and vacuum assist and via FAWJ (number in parentheses is the thickness in millimeters)



**Figure 10. Typical composite parts machined with a miniature nozzle. Numbers in parentheses are thickness in millimetre. - Scale mm/div.**

#### 4. CONCLUSIONS

With commercial aerospace and wind energy (turbine blades) being the leading drivers and microelectronics not far behind, the composites industry has seen strong double-digit growth. Since composites are not only expensive but also difficult to machine with established machine tools, there is a considerable need for a cost effective, fast turnaround, and damage free machine tool to meet the anticipated demand. Abrasive-waterjets have shown to possess inherent merits that were unmatched by most other machine tools. For patterns that do not need internal piercing, AWJs have shown to be a preferred tool for machining composites. For machining features required internal piercing, buildup of static pressure inside blind holes during the initial piercing stage tends to damage composites with weak tensile strength. Current remedies with limited success have been resorted to predrilling with an attached drill head or adopting pressure ramping together with water flushing. To mitigate piercing damage, a novel process, flash abrasive-waterjets or FAWJs (patent pending), has been successfully developed by superheating high-pressure water such that it changes phase upon exiting the nozzle. As a result, only very little high-speed liquid water enters the blind hole and buildup of large static pressure has been alleviated. Comparison of various composite samples machined with AWJs and FAWJs has demonstrated the merits of the latter in mitigating AWJ-induced damage such as delamination, cracking, and chipping.

There is a great opportunity to take advantage of the unique material independent characteristics of AWJs for machining nanomaterials that integrate optimally and seamlessly a number of materials in the molecular level. Nanomaterials are expected to be much stronger and tougher than conventional composites and their processing would present considerable challenge to established machine tools. To apply AWJs toward fabrication/processing of microelectronics, MEMS, biomedical components, and nanoproducts, considerable efforts and investment have been made to downsize AWJ nozzles. Current state-of-the-art relies on vacuum assist and water flushing to enhance the gravity feed of fine abrasives in miniature AWJ nozzles; the appendages (an ejector, a water pump, four feed ports, and tubes) to facilitate such operations significantly add to the bulkiness of the AWJ nozzle and increase the complexity in the micromachining procedure. Novel processes have been successfully developed to get around the use of vacuum assist and water flushing. Under the sponsorship of an NSF SBIR Phase I Grant, a feasibility investigation is underway to develop  $\mu$ AWJ nozzles capable of micromachining with features around 50 to 100  $\mu\text{m}$ .

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