Research Article

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Advanced Waterjet Technology for Machining Curved and Layered Structures

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Abstract: Considerable advancements in waterjet technology take advantage of its inherent merits as a versatile machine tool have been achieved in recent years. Such advancements include, but are not limited to, process automation, machining precision, multimode machining of most materials from macro to micro scales, and cost effectiveness with fast turnaround. In particular, waterjet as a cold cutting tool does not introduce heat-affected zones (HAZ) and preserves the integrity of parent materials. As such, for heat-sensitive materials, its cutting speed is over ten times faster than those of thermal-based tools, such as solid-state lasers, electric discharge machining (EDM), and plasmas cutting. Although waterjet is basically a 2D machined tool, novel multi-axis accessories were developed to enable 3D machining and for machining on workpieces with 3D geometry. For composites, waterjet unlike mechanical routers is capable of minimizing or mitigating tearing and fraying. CNC hard tools that are in direct contact with highly abrasive composite matrix often experience rapid wearing while the heat generated by machining processes induces thermal damage to the composite. This is a nonissue for waterjet as it is a noncontact tool. The only issue for machining composites with waterjet was the damage caused by large stagnating pressure developed inside blind holes during the initial piercing operation (before breakthrough). Considerable effort was made to understand and resolve the waterjet piercing damage issue. For extremely precise parts, waterjet can serve advantageously as a near-net shaping tool; the parts can then be finished by light trimming with proper precision tools. Since the bulk of the material is removed by waterjet, the operating lives of the precision tools can be greatly extended. This paper presents a collection of waterjet-machined samples to demonstrate many benefits by applying waterjet for multimode machining of curved and layered structures.

1 Introduction

Waterjet by entraining abrasives or abrasive waterjet (AWJ) was commercialized in the mid 1980s to take advantage of its inherent merits of material independence and high power of cutting [27]. At that time, it was introduced merely as a rough cutting tool. Since then, waterjet technology has improved steadily for industrial applications [31, 35].¹ One of the main enablers is the introduction of the Roctec ceramic tungsten carbide composite for fabricating reliable mixing tubes for the AWJ nozzle. Automation of waterjet machining became a reality after PC-based motion control systems were developed for precision location of the waterjet stream.² In the early 2000s, waterjet machine tools had emerged as the fastest growing segment of the machine tool industry and such a trend was expected to continue.³ According to Frost and Sullivan, the growth rate was subsequently limited by the lack of awareness of the technology. Waterjet inherently possesses several technological and manufacturing merits unmatched by most machine tools [27], including:

- A green manufacturing process that uses no toxic machining fluids and produces no hazardous byproduct
- Cold cutting that introduces no heat-affect zones (HAZ) and preserves the structural and chemical integrity of parent materials [18, 19]
 - High speed cutting
 - No need for secondary process to remove the HAZ
- Material independent for machining most materials from metal, nonmetal, composites, laminates, brittle materials, and anything in between [20]

¹ Refer to www.waterjet.org for extensive waterjet resource on the web

² U.S. Patents 5,508,596 and 5,892,345

³ (Frost and Sullivan – “The World Waterjet Cutting Tools Markets” Date Published: 30 Aug 2005 (www.frost.com))

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- Annealed and hardened steel (mitigating distortion resulting from post heat treatment)
- Non-conductive and reflective materials
- One tool assisted with accessories qualified for multi-mode machining – from cutting, facing, drilling, trimming, milling, turning, grooving, etching, and beveling/countersinking [23]
- Amenable to meso-micro machining [27]
- No direct tool contact other than the waterjet with the workpiece
 - Negligible side force exertion onto the workpiece (required only simple fixturing and induced minimum part distortion)
 - Tool wear independent of material properties

Such merits are the drivers for the rapid maturing of the technology for a wide range of manufacturing applications.

- Process automation through the development of novel Window-based CAD/CAM that is powerful but intuitive with no steep learning curve
- Precision through the incorporation of high resolution linear encoders for the traverse system and minimizing system vibration (stiff and rigid construction, vibration isolation, and matched thermal expansion of components)
- Environmental friendliness through the incorporation of a full enclosure to minimize/mitigate airborne dust and mist and to facilitate quiet (< 80db), safe, and clean operation
- Meso-micro machining capability through development of micro abrasive waterjet (μ AWJ) technology
 - Novel micro abrasive waterjet nozzles
 - Patented process for consistent feeding of fine and powdery abrasives
- Cold cutting and low side force exertion enable machining extremely thin walls/webs without thermal and mechanical distortion
- Advanced pressure controls for piercing delicate materials such as composites, laminate, and brittle materials
- Multi-axis accessories for multi-mode machining
- Precision optical locator (POL) to align the nozzle with features on parts

In essence, the waterjet is qualified with a single tool for 2D/3D machining of virtually any material from macro to micro scales with a wide range of part size and thickness. It does not induce HAZ and preserves the structural and chemical integrity of parent materials. In addition,

Window-based control software is intuitive with no steep learning curve. The above advancements have elevated waterjet as a precision machine tool often competing with lasers and EDM on equal footing. In some cases, waterjet with the above merits is often superior to lasers, EDM, chemical etching, and CNC hard tools. These tools are either material selective, part thickness limited, and/or subject to rapid tool wear. For example, cutting metals with CO₂ lasers or plasma cutter results in considerable heat damage in terms of warping, recast, and even material vaporization [18, 20]. In order to minimize the HAZ, solid-state lasers pulsed at high frequencies and wire EDM cut with multiple passes were applied successfully at significantly reduced cutting speeds. As a result, waterjet is capable of cutting heat sensitive materials over ten times faster than solid-state lasers and wire EDM [20].

Layered structures consist of composites and laminates. For machining composites, there are considerable challenges in applying CNC hard tools [5, 7]. The quality of the drilled holes for aircraft fastener in terms of roughness/waviness of its wall surface, roundness, and axial straightness of the hole section causes high stress on the rivet, leading to premature failure. The drilling process often induces microcracking and delamination, leading to significant reduction in the strength of composites. Therefore, the quality of the drilled holes can be critical to the life of the riveted joints for which the holes are used [8]. The reduction in residual mechanical properties of the drilled hole due to the stress concentration owing to the softening and resolidification of the matrix material, that has different thermal properties than the fiber, is another problem. The lower values of coefficient of thermal conductivity and temperature transition in plastics lead to thermal damages and burning of the matrix. Tool wear is a consequence of composite abrasiveness and low thermal conductivity that causes tool heating superior to what is normally observed in the drilling of metallic materials. In carbon/epoxy drilling, 50% of the energy is absorbed by the tool and the remainder is absorbed almost equally by the workpiece and chips [2]. Noticeable wear of drill bits takes place after drilling approximately 30 holes leading to frequent replacement of consumables in order to meet the precision and edge quality requirements. In other words, applying CNC hard tools could cost thousands of unnecessary dollars in tool wear and replacement.

Initial applications of waterjet to machine composites and laminates had encountered a major issue of piercing damage. The issue was due primarily to the low tensile strength (relative to metal) of composites and adhesive strength of laminates. During the initial waterjet piercing, large stagnating pressure developed at the bot-

tom of blind holes (before breakthrough). Piercing damage, in the form of delamination, chipping, and micro-cracking, results when the stagnating pressure exceeds the tensile strength of composites and adhesive strength of laminates [26]. Considerable effort has been made to investigate and solve waterjet piercing damage issue [13–16, 21, 22, 25, 26, 34]. Two proprietary processes, using low-pressure piercing vacuum assist, were subsequently applied successfully for machining layered structures without piercing damage.

Curved structures including those with 3D geometry can be made of a variety of materials from metal, non-metal (glass ceramics, composites, laminates and others), to anything in between. For safety consideration, waterjet is primarily developed for 2D machining. Multi-axis accessories and robotic platforms were developed to enable waterjet as a 3D machining.

In Section 2, a brief description of recent advancement is given on waterjet technology pertinent to machining of curved and layered structures. Section 3 describes the facilities of the apparatus for machining such structures. Samples of waterjet-machined curved and layered structures will be presented in Section 4 to demonstrate its advantages and to compare its performance with other machine tools. A brief summary, together with future applications, will be given in Section 5.

2 Technical Approach and Experimental Methods

As mentioned in Section 1, considerable advancements have been made to take advantage of the technological and manufacturing merits of waterjet technology for precision machining. Three recent advancements pertinent to machining curved and layered structures involved the development of accessories for 3D machining, novel processes for machining layered structure (composites and laminates) to mitigate waterjet piercing damage, and micro abrasive waterjet (μ AWJ) technology for meso-micro machining.

2.1 Waterjet machining

Waterjet machining relies on erosion of material by high-speed abrasives or water droplets exiting a nozzle. Water is pressurized to typically 400 MPa by a pump and forced through an orifice with small diameters to form a high-speed waterjet (WJ). The WJ breaks into high-speed

droplets upon exiting the orifice. For machining relatively soft materials such as foam and rubber, the high-speed water droplets alone are adequate. For machining hard materials, such as steel and aluminum, abrasives are gravity fed into the nozzle through a feed port. The Venturi vacuum generated by the high-speed waterjet downstream of the orifice entrains abrasives in a mixing chamber. The abrasives are accelerated through a mixing or focusing tube to form a collimated abrasive waterjet (AWJ). The speed of the waterjet forced through the orifice can be calculated according to the Bernoulli equation, or

$$V_w = V_b = \sqrt{2p/\rho} \quad (1)$$

where V_w , p , and ρ are the speed of the waterjet, pump pressure, water density, respectively [31]. At $p = 345$ MPa, the speed of the water droplets is 831 m/s according to Eq. (1). Equation (1) was validated by laboratory measurements using a dual-disk-anemometer [28]. With air entrainment, however, V_w dropped to 784 m/s, a 5.7% reduction. When abrasives are entrained into the waterjet, they are accelerated by the high-speed water droplets via momentum transfer through the mixing tube. The average abrasive speed, V_a , at the exit of the mixing tube decreases with the increase in the abrasive mass concentration (garnet was used as the abrasive). With mass concentrations of 5 and 10% (mass ratio of abrasive to water), the measured V_a were 560 and 460 m/s, respectively. The corresponding ratio of V_a versus V_w were therefore 71% and 59%. Note that the density of garnet is 4.1 times that of water. Although the garnet was accelerated to about 60% of the speed of water droplets, the kinetic energy, $\frac{1}{2}mV^2$, of a garnet particle is about 1.5 times higher than that of a water droplet of the same size. In addition, the sharp edges of garnet further enhance the erosion power.

The WJ or AWJ nozzle is mounted on a platform to facilitate machining operations. OMAX has four product lines of waterjet systems for a wide range of machining applications. The systems are controlled by a Window-based CAD/CAM for automated operations - the Intelli-MAX software suite. It consists of a cutting model that is, perhaps, the most significant factor in propelling abrasive waterjets into mainstream manufacturing. The cutting model uses sophisticated mathematical modeling to predict the precise motion and shape of the jet stream along each entity of a tool path based on the operating parameters. The cutting tool on an abrasive waterjet is a high-velocity stream of water and abrasive, known as the jet stream. Unlike rigid cutting tools, such as a CNC mill, the jet stream is a “floppy” tool that bends as it cuts, and the shape of the stream changes depending on how fast it’s moved. This means that a waterjet will tend to undercut corners and

Figure 1: Machineability and pierceability of common materials.

swing wide on curves if it's moved like a traditional, rigid cutting tool. The jet stream will react differently when cutting different material types, different thicknesses and at different speeds. In order to produce precision parts in a cost-efficient manner, motion control system must compensate for the behavior of the jet stream.

Early versions of waterjets required a lot of trial and error and a skilled programmer to adjust the jet motion to produce accurate parts. Now, advanced waterjets use cutting models that automatically predict the behavior of the jet stream and make adjustments to compensate for that behavior. A machine operator simply enters the material type, thickness, and desired edge quality for the given part file. The machine controller automatically determines and sets the optimal speed and path the cutting head will move along to cut a high tolerance part in the least amount of time. There's no trial and error and no need for a skilled programmer because all the experience and knowledge is built into the controller.

One of the built-in expert functions is the establishment of the machineability and pierceability indices M , and P , for common engineering materials. They were established based on extensive cutting tests. The larger the M and P , the faster the materials can be machined and pierced. Figure 1 illustrates typical M and P values for several selected materials. A look-up table consists of values of these indices for a collection of many materials resides in the machine controller. Currently, the 4th generation cutting model is optimized to cut accurate parts fast.

Waterjet is amenable to 3D machining but must be carried out with discretion. One of the properties of water is that the spent abrasives, 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, waterjet is not inherently suitable for 3D machining by simply mounting the nozzle on a multi-axis manipulator. Although there are such waterjet systems available commercially, their 3D capability is limited because of the difficulty in building and maneuvering a "perfect" catcher to block the spent abrasives completely from damaging the target workpieces, particularly for those with complex 3D features. 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 waterjet systems are built on top of a water tank that support the traversing mechanism. Such waterjet systems that are operating within the limitations of safety are mainly designed for 2D machining [32].

For light-duty machining, such as trimming of automobile accessories and aircraft composite components, 3D robotic waterjet systems with a waterjet cutting head mounted on a robotic arm are available [3]. One of the main advantages of such a configuration is its flexibility to approach 3D workpieces from virtually any angle and follow the contours. Its overall precision is inferior to the bridge-type platform. As such the robotic waterjet system is typically applied as a near-net cutting tool; the part will be finished by a proper precision tool.

There are processes available for assembling and machining 3D parts using a 2D waterjet platform [23]. These processes can be divided into two categories. Both categories employ a waterjet 2D platform without and with additional accessories. Those processes of the first cate-

gory rely on manipulating the 2D parts or the cutting algorithm to produce 3D geometry. For example, the manipulation includes stretching or rearranging of 2D parts, waterjet etching, cutting a part multiple times, thermal reshaping, unfolding followed by folding, layer manufacturing, and the combination of two or more of the processes.

For the second category, novel approaches have been developed to facilitate waterjet 3D machining while ensuring operational safety, by incorporating multi-axis accessories to the 2D waterjet platform [23].

Typically, there are two key accessories developed for 3D machining – the Rotary Axis[®] and the A-Jet[®]. The Rotary Axis is a robust, waterproof system that allows the waterjet to cut XYZ paths. The created 3D machined patterns can perform turning, grooving, slotting, facing, piercing, and trimming on tubes, pipes, and asymmetric 3D workpieces. The Rotary Axis is bolted to the frame of the JetMachining Center[®] facilitating submerged operations. The A-Jet is a complete software-controlled, multi-axis accessory permitting the flexibility to cut severe angles to a maximum of 60° off the vertical. It cuts countersunk holes and jigsaw puzzle-type pieces with beveled edges. The accessory supplies additional axes of motion, allowing the operator to fabricate and shape metal edges for weld preparation. By combining and synchronizing the operations of the Rotary Axis and A-Jet, very complex 3D geometry can be machined.

The four product lines of OMAX's waterjet machines, the OMAX, MAXIEM[®], GlobalMAX[®], and ProtoMAX[®], were controlled by a Window-based Intelli-MAX[®] Software Suite that is multifunctional and intuitive without a steep learning curve. The **LAYOUT** is Window-based CAD software for designing the tool paths for 2D parts. The design can be conducted online or offline at the pc-based terminal or imported from results created by other commercial software program such as SolidWorks, Rhino, AutoCAD, and many other CAD software. While the part is being designed, the edge quality level from Q1 through Q5, with Q5 as the best quality, is assigned to each of the cut edge. The final step of the design stage is to create the tool path of the drawing. The pathed drawing is then passed onto **MAKE**, the Window-based CAM software, for compiling the tool path into machine language. The compilation process includes setting up the JMC for the machining of the part. The setup procedure includes the selection of various parameters such as material type and thickness, the nozzle size and type (with or without abrasive), the abrasive size and mass flow rate, the event and relay timing to control the on-off of the high-pressure valve, and the motion of the traverse and other pertinent setups. After the setup is completed, all it takes is to push the start button

to machine the entire part automatically without the operator's intervention.

The **LAYOUT** of the Intelli-MAX software suite includes a feature that lets the operator inputs "extra" data for any entity in a drawing or tool path. It is called XData, short for extra data. It's great for doing things like specifying pause points, adding a note for the machine operator to display on the screen, or customizing the cutting speed for a specific entity. XData can also be used to control custom accessories like the tilting of the A-Jet cutting head and rotation of the Rotary Axis for 3D machining. In essence, when the Rotary Axis and the A-Jet are activated, XData converts the linear Y axis into a rotary axis for 3D machining. Adding XData is fast and easy. With a tool path open in **LAYOUT**, select an entity and 'XData' from the top menu, then select 'Edit XData for Selected'. The operator can then choose a command from a drop-down list and input a value for the selected entity. The XData will be added to that entity and displayed in **LAYOUT** with both an icon and a text description. **MAKE** takes the XData and applies it to the cutting path. Even if the entity is modified later, the XData will remain in place.

2.2 Machining of delicate materials

Delicate materials are referred to those that are inhomogeneous in structural and thermal properties, weak in tensile and/or compression strengths, brittle, and sensitive to heat damage. For example, the inhomogeneous composites with and without fiber reinforcement are weak in tensile strength and prone to heat induced damage. Laminates are generally weak in the adhesive strength between layers. Glass, particularly tempered glass, and silicon wafer are brittle. Proper selection of tools is essential to machine these delicate materials such that the structural and chemical properties of the parent materials are not altered or subject to various damage. Frequent damage include delamination, microcracking, chipping, and shattering.

As described in Section 1, there is considerable challenge in machining layered structures such as composites and laminates with traditional machining tools. First of all, composites are mostly nonconductive and the use of EDM is out of the question. The inhomogeneity of composites presents difficulty to lasers, particularly for material thickness exceeding 2 to 3 mm (Hoult, 2014). Current practice uses CNC hard tools for machining composites. As discussed in Section 1, rapid wear of tools, poor edge quality of the mechanically drilled holes, and thermal damage to

the matrix are among the issues that are yet to be resolved [2, 5, 7, 8].

In view of the difficulty in machining layered structures with traditional machine tools, the authors and his colleagues launched investigation by applying waterjet for machining composites and laminates. One of the earliest work was to apply waterjet for 2D to 3D machining of non-metallic (and metallic honeycomb panels [15]. The honeycomb panels were Boeing floor panel material or floorboards consisting of either a Nomex or an aluminum honeycomb core and either fiberglass or Kevlar facesheets. The thickness of the floor panel material ranges from 10 mm to 38 mm. Stainless steel and titanium honeycomb core sheets primarily consisted of 25 mm thick with 3 mm and 4.8 mm cell sizes, respectively. The titanium honeycomb provided by Boeing was designed for the NASA's High Speed Research (HSR) program and specifically for the High-Speed Civil Transport (HSCT).

For nonmetallic honeycomb panels, the performance of waterjet was considerably better than that of a mechanical router. The router induced considerable tearing on the fiberglass facesheet and on the edges of the Nomex core whereas the waterjet-cut counterparts were clean. The waterjet mounted on a 5-axis PAR manipulator was used to machine 2D profiles on the nonmetallic honeycomb panels and 3D bevels on the stainless steel and titanium honeycomb panel with good edge quality.

Subsequently, waterjet was applied to machining internal features in composites [13]. Before machining internal features, waterjet piercing must be conducted as first step. It turned out that waterjet piercing, a complex process including fluid-solid and solid-solid interactions in complex three-dimensional space with rapid evolving shape and boundaries, induced considerable damage to the composites and laminates in terms of delamination and cracking. It was discovered that a large stagnating pressure was developed near the bottom of the blind hole during the initial piercing operation before breakthrough took place [25]. Damage of the composites and laminates resulted provided the stagnating pressure exceeded the tensile strength of the composites or the adhesive strength of the laminates. Experimental and CFD modeling of piercing composites were conducted by [34]. It was demonstrated that the hydraulic shock ('water hammer') associated with liquid jet impact also contributed to the delamination of composites. A remedy was to lower the pump pressure to reduce the stagnating pressure such that the tensile strength of composites or the adhesive strength of the laminates was not exceeded.

Two novel fluidjets were developed to investigate alternate remedies for mitigating piercing damage induced

by waterjet. The first fluidjet was the abrasive cryogenic jet (ACJ) using liquefied nitrogen as the working fluid [28]. The liquefied nitrogen evaporated upon exiting the nozzle, only the high-speed abrasives entering into the blind hole to remove the material. As a result, there was very low stagnating pressure developed inside the blind hole. Piercing of a variety of composites and laminates without damage was successfully demonstrated by using the ACJ [16]. The use of the liquefied nitrogen at cryogenic temperatures was too detrimental to the components of the high-pressure pump. For example, the high-pressure seals operated for less than an hour before they had to be replaced.

A flash abrasive waterjet (FAWJ) by superheating the waterjet just before the nozzle was developed to simulate the ACJ as the super-heated water evaporated upon exiting the nozzle (US Patent No. 7,815,490). Again, only the high-speed abrasives entering into the blind hole to remove material. Minimum stagnating pressure, if any, was built up inside the blind hole. The FAWJ was applied successfully to pierce and machine parts made from various composites and laminates without damaging the parts [26]. The FAWJ that required a significant amount of energy to raise the temperature of water above boiling temperature just upstream of the nozzle was not a practical remedy to mitigate the waterjet piercing damage issue.

The test results derived from machining composites and laminates using the ACJ and FAWJ have clearly confirmed that large stagnating pressure was the cause of piercing damage to composites and laminates. Based on that finding, two proprietary processes, the Turbo Piercer and Mini Piercer were developed for piercing delicate materials with relatively large and small hole diameters, respectively. The Turbo Piercer that employed large nozzles modified the jet stream to reduce the stagnating pressure whereas the Mini Piercer that used the micro nozzles and low-pressure piercing to achieve the same effect. For the Mini Piercer, the combination of low pressure and small orifice reduced the Venturi vacuum to the level that only a portion of the abrasive fed from the hopper was entrained into the mixing tube, leading to clogging of the micro nozzle. A vacuum assist device must be employed to help boost the low Venturi vacuum and mitigate nozzle clogging.

2.3 Micro abrasive waterjet technology

Waterjet is amenable to micromachining as its diameter can be downsized to tens of microns [30]. Under the support of a US National Science Foundation (NSF) Small Business Innovative Research (SBIR) grant, OMAX devel-

oped and commercialized micro abrasive waterjet (μ AWJ) technology, culminating an award-winning MicroMAX[®] Jet-Machining Center.⁴ The MicroMAX is one of the most precision waterjet machines for precision meso-micro machining [18–20].

With the MicroMAX added to the product lines of OMAX waterjet systems, we have established the full capability of precision Multi-Mode Machining of Most Materials from Macro to Micro scales for a wide range of part sizes and thicknesses – the “7M” advantage of waterjet.⁵ The samples of waterjet-cut curved and layered structures of a broad range of part size and thickness presented in this paper were machined with several waterjet systems with different foot prints.

3 Facilities and waterjet components

There are two laboratories and one manufacturing cell equipped with several waterjet systems. The R&D Laboratory is equipped with one OMAX 2626, two OMAX 2652, one MAXIEM 1515, one GlobalMAX 1530, and one ProtoMAX.⁶ The Demonstration Laboratory is equipped with one MicroMAX, one OMAX 2652, One OMAX 60120, and one MAXIEM 1515. The Waterjet Manufacturing Cell is equipped with one OMAX 55100, OMAX 5555, and one OMAX 60120. A number of these machines are equipped with accessories for 3D machining. The R&D Laboratory is designated for conducting R&D cutting to improve and optimize the system and component performances. The Demonstration Laboratory is to conduct demonstration cutting for perspective clients. The Waterjet Manufacturing Cell is to machine parts that are used to assemble the four product lines of waterjet machines. With the waterjet integrated into our manufacturing production lineup, we were able to achieve 35% saving of manufacturing costs together with minimizing inventory while engaging “Just in time” lean manufacturing practice.

The MicroMAX and the OMAX 160X have work envelopes of 0.64 m x 0.64 m and 6.1 to 14.2 m x 4.06 m, respectively. Figure 2 illustrates photographs of the three accessories – Tilt-A-Jet (TAJ), Rotary Axis, and A-Jet. The TAJ was designed for compensating the edge taper resulting

from the spread of the waterjet stream and the degradation of cutting power with the depth of cut. The Rotary Axis and A-Jet were designed for 3D machining.

Figure 2: Three Accessories

There are a set of nozzles for machining parts from macro to micro scales. Figure 3 illustrates several standard ones that are commonly used. The three on the left are the abrasive waterjet (AWJ) nozzles and the right most one is the water-only (WJ) nozzle. The numbers in the parentheses are the diameters of the orifice and the mixing tube in thousandth of an inch, respectively. All the nozzles have the same length as the tip of the nozzle is the tool center point (TCP) for the A-Jet. The TCP is the pivoting center of the TAJ and the A-Jet and is fixed in position for all angles of tilting.

For extremely delicate materials with very low tensile strength, a mechanical drilling head consisting of a drill bit is available to be attached to the waterjet system. Piercing of the part is performed prior to machining any internal features. A position optical locator (POL) as illustrated in Figure 2a is used to reposition accurately the nozzle to the centers of predrilled holes.

⁴ The MicroMAX was named a Finalist of the 2016 R&D 100 Awards (<https://www.sbir.gov/node/1308555>)

⁵ <http://www.mdpi.com/2504-4494/1/1/11/pdf>

⁶ <https://www.omax.com/products>

Figure 3: Waterjet nozzles.

4 Results

In this section, waterjet-machined samples are presented to demonstrate the versatility of waterjet for machining curved and layered structures. The JMC was set up according to the material type and property, the part geometry, and required accuracy. For 2D parts, there is no need to activate the Rotary Axis or the A-Jet. Because waterjet spreads after it exits the nozzle and the cutting power decreases with the depth of cut, there is a natural taper on the waterjet cut edge. A dedicated accessory Tilt-A-Jet (TAJ) is specifically designed to compensate for the edge taper.⁷ The TAJ is similar in design to the A-Jet except that it has only a tilting range of ± 9 degrees. With the TAJ activated, nearly taper free edges can be machined.

The Rotary Axis is designed for machining operations required rotational manipulation of the workpiece. The A-Jet is used to machine 3D features on workpieces, particularly for non-flat stocks. By combining the Rotary Axis and A-Jet, complex 3D features required 6-axis movement can be readily machined. Refer to Section 2.1 for the operations of the Rotary Axis and A-Jet for 3D machining.

4.1 Machining curved structures

4.1.1 In-plane curve features

Novel flexure-based nonlinear load cells that were highly sensitive with 1% change in the force and five orders of magnitude in the force range were developed and patented at MIT for precision force measurements (US patent #20150233440). For detailed theory and function-

(a) Constant-width flexures [20]

(b) Comparison of AWJ-machined flexure with its design

(c) Tapered flexures [19]

(d) Comparison of AWJ-machined flexure with its design

Figure 4: Aluminum nonlinear load cells.

ality of the load cells, refer to [9, 10]. Two of the load cells consisted of large-aspect-ratio flexures with constant and variable width. The edges perpendicular to the planes of the load cells are nearly taper-free. The third load cell used two steel springs as the flexure. The nearly taper-free flexures present considerable challenge to traditional machine tool as the induced heat of lasers and EDM and the relatively large side force exerted on the workpiece by CNC tools would cause the thin flexure to bend and distort.

⁷ <https://www.omas.com/accessories/tilt-a-jet>

The author collaborated with the Precision Engineering Research Group (<http://pergatory.mit.edu/>) and Mechanical Engineering Department to machine several aluminum prototypes of the load cells using the MicroMAX with the 7/15 nozzle (orifice and mixing tube IDs: 0.18 mm and 0.38 mm). The pump pressure was set at 380 MPa; 220 mesh garnet with a mass flow rate of 45 gm/min was used. The TAJ was activated to enable achieving nearly taper-free edges of the thin flexures, a critical factor to meet the required precision and repeatability of the load cells. Figure 4 illustrates photographs of two waterjet-machined load cells. Figure 4a illustrates the one with four large aspect-ratio (98.3) and constant-width (1 mm wide) cantilever flexures. Each one consists of a moment compliant “19.1 mm diameter ring” connector. At low forces, the full lengths of the four flexures serve as the elements to achieve the high sensitivity. At high forces, the flexures bend and rest on the stops of the load cells. The lengths of the sensing elements reduce to about one half of the full length enabling the load cell to measure large forces without over straining the flexures. The cold cutting of waterjet and its negligible side force exerted on the workpiece are the keys to the success in machining such large-aspect-ratio thin and curved flexures without thermal- and mechanical-induced distortion. Figure 4b illustrates the comparison the micrograph of upper right waterjet-machined flexure with the design drawing (magenta outline). There is minimum, if any, distortion of the overall geometry in the straight and circular segments. Even the detailed geometry matches well with that of the Designed drawing. The load cell illustrated in Figure 4c has four tapered flexures. Other than the differences in the geometry of the two flexures, the same nonlinear principle applies to both for high sensitivity and large force range. Note that the tapered flexures at the points of connection to the body of the load cell has a minimum width of 0.5 mm. Figure 4d illustrates the micrographs of upper right flexure at the end with the minimum width. The magenta outlines are the design drawing. The right and left micrographs correspond to the flexure on the jet entry and exit sides, respectively. Again, the waterjet-machined flexure match well with both the overall and detailed geometry of the designed counterpart. The above results demonstrate that the TAJ performed well in minimizing the taper of the vertical edges. Machining such thin flexures with nearly taper-free edges while maintaining their design geometry without distortion presents considerable challenge to traditional machine tools. The heat generation and/or the side force exertion during machining are expected to cause permanent distortion or deflection of the thin flexures, leading to degradation of the part precision and performance.

The performance of the two load cells were subsequently conducted through several series of laboratory tests at the MIT laboratory. The results agreed well with the theory [9, 10].

4.1.2 Out-of-plane curved features

The Rotary Axis facilitates machining features that require rotary movement of the workpiece. The machining operations include, for example, cutting, facing, trimming, turning, grooving, milling/etching, and others. First, two-dimensional CAD drawing of the part is made in **Layout** with the y-axis to be converted into the rotary axis via the XData command. For example when machining features on a tube or pipe, the length of the part in the y-axis is set to πD where D is the OD. During machining, features specified on the y-axis will be cut on the perimeter of the tube or pipe as it rotates.

Figure 5 illustrates several AWJ-machined parts cut on stainless steel (larger two) and titanium (smallest one) tubes, with ODs equal to 25.4, 22.2, and 6 mm, respectively. The tubes were mounted on the Rotary Axis. Sacrificial carbide rods were inserted in the tubes to protect the opposite wall from damaged by the spent AWJ after the features on the top wall was cut. The features machined on the vertical tube are rigid and those on the two other tubes are bendable interlocking links. Zoomed-in segments of the interlocking links for the small titanium “necklace” and the large stainless tube are shown on the top right and lower right corners of the figure, respectively. The interlocking links may be difficult to machine with other tools.

Figure 5: AWJ-cut parts with the use of the Rotary Axis.

A novel low-resistance slot-less armatures for a high-efficiency motor/generator, as illustrated in Figure 6, was developed at the Precision Engineering Research Group at MIT [37]. The device has the potential for developing new electric armatures to increase the efficiency of electric motors in many consumer and industrial applications. The key components are two slotted copper tubes (Figure 6b) that serve as the stator and rotor. The μ AWJ was the only tool that could be used cost effectively to machine the slot-less copper tubes since lasers cannot cut copper because of its high index of refraction while the nonsymmetrical patterns of the slots present considerable challenge to EDM. The designed width of the slots on the copper tubes was 0.38 mm. There were machined using the 5/10 nozzle and the 240 mesh garnet with a mean particle diameter of 60 μ m.

Figure 6: μ AWJ-machined slot-less armature [37].

Figure 7 illustrates a part machined on the Rotary Axis to take advantage of the low force exertion on the workpiece by the waterjet. The 173 mm long part consists of twelve spiral segments machined on a 9.4 mm OD steel rod. The steel rod was mounted on the Rotary Axis with an overhang of 200 mm. Machining started at the cantilever end of the rod and finished at the opposite end.

The versatility of waterjet with its merits of material independence, cost effectiveness, and fast turnaround has begun penetrating the biomedical manufacturing sector [17]. The author has aggressively advocated applying waterjet for manufacturing orthopedic implants, particularly for patient specific applications. The importance of manufacturing patient-specific implants (PSIs) cannot be overstated in the world of orthopedics and prosthetics. PSIs offer very real benefits such as better surgical quality and comfort level to patients, and cost effective with reduced inventory. They are also facing considerable challenges as the PSI market moves ahead.⁸ Waterjet has the potential to ease much of the challenges

1. At present, PSIs are labor intensive for manufacturers - Custom, one-off implants mean production runs of exactly one unit rather than hundreds with off-the-shelf or OTS implants. One of the most labor-intensive steps to the process is to convert patient data into manufacturing inputs, primarily a manual process. Manufacturing a one-off and used-one device likely means one-off tooling as well since every patient is a little bit different. The tool-less waterjet would ease the labor intensive concern.
2. Hospitals have limited contingencies - One implant means one chance to get it right. There are limited contingencies in OR. If a device gets damaged there's not a backup. Multiple backup devices can be fabricated with waterjet to take advantage of its fast turnaround time.
3. OTS implants are readily available - Right now if a doctor wants an OTS implant he/she can get one almost immediately. Not at all true for PSIs yet. As such manufacturers of PSIs are under huge pressure to have a quick turnaround. At present, companies are turning implants out comfortably in 5 – 6 weeks and getting it down to 4 weeks. With waterjet, the turnaround time could reduce to two to one week or even sooner.

Demonstration has been made to apply AWJ machining of metallic and PEEK biomedical components such as the titanium and nitinol mesh cage that provides structural support to the anterior column as a part of the reconstruction procedure after thoracolumbar corpectomy [1]. The mesh cage can be readily machined by mounting a titanium tube on the Rotary Axis. Figure 8 illustrates an array of diamond-shaped holes machined on a stainless

⁸ <https://www.mddionline.com/patient-specific-implants-seven-things-you-should-know>

Figure 7: Twelve spiral segments machined on a 9.4 mm OD steel rod with the Rotary Axis.

Figure 8: Diamond holes and metal mesh cages.

Figure 9: AWJ-machined stents with three different web widths.

steel plate 0.4 mm thick, a titanium mesh cage by machining with the Rotary Axis the same hole pattern onto a 6 mm OD titanium tube. On the right is a nitinol mesh cage with an OD of 14.8 mm.

Another potential application using the Rotary Axis is to machine metal stents, small mesh tubes made from nitinol or titanium for treating narrow or weak arteries. The procedure of placing a stent in an artery is often a part of a percutaneous coronary intervention (PCI) that restores blood flow through narrow or blocked arteries [36]. Stents may also be placed in weak arteries to improve blood flow and help prevent arteries from bursting. Figure 9 illustrates several waterjet-machined stents made of stainless steel. Nitinol an alloy of nickel and titanium has the properties of superelasticity and shape memory. Superelasticity refers to the enhanced ability of a material to be deformed without irreversible change in shape. Shape mem-

ory is the ability of a material to regain its shape after plastic deformation at a lower temperature. Such properties are particularly suitable for self-expanding stents [12]. With a machineability of about 50 for Nitinol (80 for stainless steel – refer to Figure 1), waterjet is a preferred tool for machining this material. Using the Rotary Axis, the time to cut the stent made of Nitinol is less than 10 minutes.

One of the steps for implantation of orthopedic components is sterilization. For waterjet machined parts, embedded abrasives must be removed or completely sealed to ensure biocompatibility. Several secondary processes to sterilize orthopedic components are available. They include but are not limited to glass-bead blasting and deburring, acid washing, electro-polishing, and passivation. Cleaned components are further sterilized with autoclave, gamma irradiation, oxygen plasma, or ultraviolet light. Recently, it was discovered that polycrystalline diamond (PCD) can be applied to coat implants with multiple benefits [33]. PCD coating could be applied for completely sealing off residual abrasives on waterjet-machined implants.

For machining features on 3D workpieces such as spherical surfaces, the A-Jet capable of tilting up to 60 degrees off the vertical axis can be readily applied. Figure 10 illustrates a photograph of the global map of the north hemisphere cut on a hemispherical steel shell with a diameter of 0.3 m and a thickness of 1.5 mm. The dark blue and light green areas represent the ocean and land, respectively. The file started as a black and white image of the world continents. OMAX Intelli-TRACE was used to create a two-dimensional path that was then interpolated onto a three-dimensional sphere using Rhino 3D or another three-dimensional CAD software.⁹ The world map was cut in half and trimmed, keeping the desired sections of the map (the north hemisphere). The surface was then given a thickness the same as the hemispherical steel shell. The 3D CAD file of the world map was then exported in the STL format that was imported into Intelli-CAM and a path was generated for the map.⁶ Next, the hemispherical steel shell was loaded and secured on the platform of the 60120 JMC. The map was ready to be cut by picking a starting point.

⁹ Intelli-TRACE and Intelli-CAM are a part other Intelli-MAX software suite (<https://www.omax.com/software>)

Figure 10: AWJ-machined map of North America on steel hemisphere.

Figure 11: AWJ-machined soccer ball.

Figure 11 illustrates an AWJ-machined soccer ball by welding together two hemispherical halves using the same material shown in Figure 10.

Combining the operation of the Rotary Axis and the A-Jet facilitates machining complex 3D parts. One of the examples is to machine “fish mouth” weld joints for pipes and tubes [29]. Figure 12 illustrates several such weld joints that are weld ready. Also shown in the figure are two welded steel tubes with different diameters. Weld joints machined with the cold cutting waterjet need no secondary processing such as grinding away the damaged HAZ before welding. For large pressure vessels, curry practice uses plasmas cutter to cut segments of the vessel. Time consuming hand grinding is often used to remove the damaged HAZ as a part of the weld preparation process.

4.2 Machining layered structures

Waterjet is a preferred tool for machining most composites provided piercing of small holes is not required. The common practice for machining composites is to pierce and then cut the materials at low and high pressures, respectively. Figure 13 illustrates photographs of a collection of eight AWJ-machined composite parts. The corresponding composite materials shown in the figure are (1) fiberglass, (2) G10 garolite, (3) carbon fiber, (4) G10 Garolite – black, (5) FR4 laminate, (6) plastic, (7) phenolic, and (8) polycarbonate.

4.2.1 Turbo and Mini Piercers

As discussed in Section 2.2, considerable efforts were made to develop novel waterjet processes for machining delicate materials such as composites, laminates, and various glass materials. The key is to reduce the stagnating pressure during initial piercing of the materials such that the tensile or the adhesion strength of those materials were not exceeded [13, 16, 26]. The working fluids of these two the ACJ and FAWJ evaporate upon exiting the nozzle. Since there was only a very small amount of high-speed working fluid entering the blind hole, the stagnating pressure at the

Figure 12: AWJ-machined “fish mouth” weld joints on stainless steel tubes facilitating welding of two small tubes onto a larger counterpart.

Figure 13: Collection of AWJ-machined composite parts.

(a) Top view

(b) Side view

(c) Micrographs

Figure 14: AWJ-drilled holes on G10 composite without and with Turbo Piercing.

bottom of the blind hole was so low that the tensile or adhesive strength was not exceeded.

Two novel processes, Turbo and Mini Piercers, were developed based on the findings derived from the test results of the ACJ and FAWJ [13, 16, 26]. The Turbo Piercer modifies the AWJ within the nozzle to reduce the speed of the water droplets exiting the nozzle. As a result, the kinetic energy of the water droplets is considerably lower than those of the unmodified AWJ. The lower the kinetic energy leads to lower stagnating pressure as the kinetic energy converts into the potential energy at the bottom of the blind hole. The process of modification results in increase in the spread of the AWJ; the Turbo Piercer was most suitable for machining features with relatively large kerf width. Figure 14 illustrates the top (a) and side (b) views of AWJ-drilled holes on G10 composite sheets. The dimensions of the round and square parts were 76.2 mm in diameter and 63.5×63.5 mm and 8.4 and 25.4 mm thick, respectively. On the left was a single hole drilled with the traditional AWJ. The stagnating pressure induced in the bottom of the blind hole clearly exceeded the tensile strength of the laminated composite, leading to severe multilayered delamination. When the Turbo Piercing process was activated, a total of 196 holes (1.3 mm ID) at close proximity

Figure 15: Small hole drilled with Mini Piercer on aluminum laminate.

were drilled successfully without any delamination. Figure 14c compares the corresponding micrographs of the cut-off edge around the hole on the delaminated round disk and the same edge with no delamination.

Figure 15 illustrates two sets of holes drilled on aluminum laminates using the Mini Piercer. The 1.5 mm thick laminates consisted of 19 layers of 0.76 mm thick aluminum shims. Three nested square patterns 9.1×9.1 mm) with six small holes of 0.55 mm ID were drilled with the 5/10 nozzle using the 240 mesh garnet. Narrow tabs were left on the nested squares to keep them from falling off into the catcher tank. These holes drilled with low-pressure piercing. At pressure < 140 MPa, the Venturi vacuum created by the high-speed waterjet in the mixing chamber just downstream of the diamond orifice was too low to entrain all the abrasive fed from the hopper. As a result, the excessive abrasives accumulate in the mixing chamber and lead to nozzle clogging. Vacuum assist was used to boost the vacuum inside the mixing chamber. A part of the abrasives were removed through the vacuum assist bypass. Note that the vacuum assist process does not disturb the flow through the mixing tube and the AWJ remains well collimated. Piercing of the small holes were conducted by using a range of low pump pressure to determine the threshold pressure level required to mitigate delamination. For example, the hole patterns on the left photographs were pierced at 69 MPa. Delamination appeared

while piercing one of the holes inside the middle square. Such a pressure is on the border line such that the stagnating pressure induced was close to that of the adhesive strength of the laminate. Delamination took place at spots where the adhesive strength was lower than the stagnating pressure. Subsequently, the pump pressure reduced to 52 MPa and no delamination was mitigated, as shown in the right photograph.

For machining features on very thin sheets that are extremely delicate, it is very challenging to design a viable fixture to secure the sheets firmly for machining. Turbo and mini piercing can be taken advantage of for stack machining to resolve the fixturing issue while offering other advantages.

- With the TAJ activated to minimize the edge taper, multiple thin parts can be machined precisely and cost effectively with fast turnaround
- The top sheet serves as a sacrificial protective cover to removal of edge rounding and frosting on the sheets below

Figure 16 illustrates an AWJ-machined part made of the same aluminum laminate described above. The Mini Piercer used the 5/10 nozzle and 240 mesh garnet. Figures 16a and 16b illustrates the top and side views of the part. Figure 15c illustrates four of the individual sheets separated from the stack by soaking it in a solvent. The machined features of the four individual parts were precisely matched.

4.2.2 Cranial implants

For cranial implants, titanium has been primarily used as the biomedical materials in the past [4]. A relatively new biocompatible composite material, Polyether-Ether-Ketone (PEEK), has been shown to be a superior replace-

ment of titanium implants in terms of avoidance of allergic tissue reaction to metallic ions and transparency to X-rays [11]. A strong trend has been established that the demand for high performance PEEK implants has been steadily increased. As described in Section 4.2.1, OEM manufacturers often have limited size selection on OTS implants. While several manufacturers have begun manufacturing PSIs, many issues and challenges remain.

The technological and manufacturing merits of waterjet in terms of cost effectiveness with fast turnaround, cold cutting capability, simple tooling requirement, and qualification for multimode machining with a single tool, are especially suitable for manufacturing of various implants, particularly for patient specific applications. Considerable efforts were devoted to demonstrate the capability of waterjet for manufacturing prosthetic and orthopedic devices. Test cutting was conducted to machine cranial implant models readily accessible online. PEEK was chosen as the materials as cranial implants can be cut in 2D and then converted into 3D counterparts by thermal reshaping. Figure 17 illustrates the top and side view of two thermally shaped cranial implants made from unfilled (skin color) and fiber-reinforced (black) PEEK. The implants 62 mm OD with 5 mm ID holes were initially machined with waterjet on a flat stock 2 mm thick. Fixation holes with an angle of 40° from the vertical were then machined using the A-Jet. The cutting time is less than five minutes. 2D implants were then baked in an oven at 300°C for about one to two hours using a 200 mm diameter steel hemisphere as the mold. There are at least two options, fixation plates and screws, to fixate the implants onto a skull. Figure 18 illustrates the use of stainless steel screws to fixate the implants onto a model skull. Note that the waterjet machining and thermal shaping times are no longer than several hours. For patient specific applications, getting the patient's CT data and applying secondary pro-

Figure 16: AWJ stack machining of aluminum laminate.

Figure 17: PEEK cranial implant models with a 200 mm diameter spherical profile.

Figure 18: Fixation of PEEK cranial implants onto adult model skull.

cesses to sterilize the implants are expected to be the most labor intensive and time consuming.⁷.

5 Conclusion

A rich collection of waterjet-machined parts was presented to demonstrate the versatility of the technology for machining curved and layered structures. Waterjet inherently possesses technological and manufacturing merits that are unmatched by other tools. The goal was to emphasize its full capability of precision multimode machining of most materials from macro to micro scales, the “7M” advantage, for a wide range of part sizes and thicknesses. Basically, waterjet is primarily a 2D machine tool when operational safety is taken into consideration. Multi-axis accessories together with smart Window-based CAD/CAM software were developed to elevate waterjet to become a highly automated 3D machine tool. Novel processes were also developed to overcome issues such as waterjet piercing damage to delicate materials with weak tensile and adhesive strengths. Among the technological and manufacturing merits, cold cutting, material independence, fast material removal rate, cost effectiveness with fast turnaround, and low side force exertion are most advantageous. For heat sensitive materials, waterjet is capable of outperforming most thermal-based machine tools by one order of magnitude in the cutting speed. Since waterjet requires no tooling, it is equally cost effective for small-and large-lot runs from R&D, prototyping, to 24-7 production. Waterjet has been adopted for a variety of manufacturing applications, including but is not limited to automotive, aerospace, oil and gas, electronic, jewelry, and biomedical. In particular, the merits of waterjet can be fully taken advantage of for

manufacturing patient specific orthopedics and prosthetics with a wide range of size and geometry. This would help streamline the surgical procedure, leading to expediting turnaround and reduction in inventory and in healthcare costs while accelerating the healing cycle. In addition, mobile waterjet systems are readily available and they can be potentially deployed in remote locations to serve the under privileged population.

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