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Paper

APPLICATION OF ABRASIVE-WATERJET FOR 3D MACHINING

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ABSTRACT

Abrasive-waterjet (AWJ) is inherently not suitable for complex 3D machining because of the difficulty in capturing the spent abrasives in a three-dimensional space. The spent abrasives still possess considerable residue cutting power that is not only capable of damaging the target workpiece but also a potential safety hazard to the operators. Designing an optimum catcher for a 3D AWJ system to mitigate damage to the target workpiece with complex 3D features is nearly impossible. Although there are commercial multi-axis 3D AWJ systems, they are only limited to machining relatively simple 3D parts. On the other hand, AWJ is amenable to 3D machining. Approaches to take advantage of the 3D machining capability of AWJ while operating within the limitations of safety are discussed in this paper. Generally, the approaches can be divided into two main categories, those with and those without the requirement of added accessories, respectively. For the approach requiring no additional accessories, the workpieces have to be cut multiple times at different orientations or rely on secondary processes to transform them from 2D to 3D shapes. For a number of applications, special accessories were designed to be mounted on the 2D AWJ platform to facilitate 3D machining. PC-based control software was developed to control the operations of these accessories for automation. Machining processes based on these approaches were developed to facilitate 3D machining using a 2D AWJ platform such that the spent abrasives were always shooting in a generally downward direction toward the machine's water tank. By combining more than one accessory, 3D parts with very complex features can be readily machined. Sample 3D parts machined with the above processes are presented to demonstrate the versatility and advantages of AWJ 3D machining.

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1. Introduction

Abrasive-waterjets (AWJs) have several technological and manufacturing merits that are superior to most existing machine tools. Such merits are the direct results of the versatility of the waterjet technology, including but not limited to:

- Cut virtually any material (reflective/nonreflective, conductive/nonconductive, and annealed/hardened, etc.)
    - cut metals, ceramics, stones, composites, PEEK, laminates, and brittle materials
    - cut titanium 34% faster than stainless steel
- Cut a wide range of size - from macro to micro scales (large, small, thick and thin)
- Fast setup and programming – modern systems are now easy to learn (no steep learning curve)
- Simple fixturing – negligible reactionary forces on parts
- Amenable to multiple dimensional machining (cutting, trimming, drilling, routing, turning, milling, beveling, countersinking, and others)
- Preserve structural and chemical integrity of raw materials
    - cold cutting – no heat-affected zone (HAZ) and surface hardening
    - no residual mechanical stresses
- Safe operations
- No start hole required – one single tool for multi-mode machining
- Narrow kerf – removal of only a small amount of material
- Cost-effective and fast turnaround for both small and large lots
- Environmentally friendly –
    - no dust and low noise (when cut submerged)
    - no hazardous waste byproducts

Recent advancements in automation, precision, and control have elevated AWJs as mainstream machining tools competing on equal footing with CNC tools, laser, EDM, and others. In certain specific applications, AWJ is the only cost-effective tool to complete a job. The versatility of AWJ has greatly increased its market share as a precision machine tool.

AWJ is amenable to 3D machining but must be carried out with discretion. One of the properties of AWJ 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, AWJ is not inherently suitable for 3D machining by simply mounting the nozzle on a multi-axis manipulator. Although there are such AWJ 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 AWJ systems are built on top of a water tank that also serves to support the traversing mechanism. Such AWJ systems that are operating within the limitations of safety are mainly designed for 2D machining (Olsen, 2012).

Novel approaches has be developed to facilitate AWJ 3D machining while ensuring operation safety, by either manipulating the workpiece or incorporating accessories to the 2D AWJ platform (Olsen, 2012). This paper presents several machining processes that adopt such approaches to broaden the utility of a 2D AWJ platform for 3D machining. 3D sample parts cut with these processes are presented to demonstrate the extended applications of 2D AWJ platforms for 3D machining.

2. Technical Objectives

The overall technical objective of this paper is to describe the capability of machining 3D parts using a 2D AWJ platform. Several processes to facilitate cutting 3D parts on a 2D AWJ platform are examined and presented. The effectiveness of these processes for AWJ 3D machining are assessed and demonstrated by showing selected images of AWJ-cut 3D parts.

3. Technical Approach and Facilities

3.1 Technical approach

The technical approach is to apply several processes designed to machine 3D parts on a 2D AWJ platform. One of the main requirements is to operate 3D AWJ machining within the limitations of safety (Olsen, 2012). Collectively, these processes facilitate the use of the 2D AWJ platform for machining of a variety of 3D parts. Some processes require only additional cutting by reorienting the same workpiece with respect to XY traverse of the nozzle. Others require further processes to transfer the 2D part into 3D parts. Yet others require added accessories or ancillary devices designed to machine specific 3D features on the workpiece. Furthermore, combining more than one process or accessory would allow the machining of 3D parts with very complex features.

Based on the technical approach described above, several processes have been developed to machine 3D parts using a 2D AWJ platform. These processes include but are not limited to

- Arrange/stretch a 2D part into 3D shape.
- Cut a part multiple times with the workpiece set to a different orientation for each additional cut.
- Cut a 2D part first and then form the 3D final shapes by secondary processes (e.g., mechanical or thermal folding).
- Unfold via unfolding software a 3D part into 2D components, cut the components, and reassemble them by folding these components back into the 3D shape.
- Slicing 3D parts into layers, machine the layers, and reassemble the 3D part by an orderly stacking of the individual layers. Layer machining is often an effective means to machine 3D parts with complex internal features.
- Develop special accessories and ancillary devices mounted on the 2D AWJ platform. Each accessory and/or ancillary device is designed to machine a certain 3D feature. Combining the operations of more than one accessory and/or ancillary device would facilitate cutting 3D parts with complex features

3.2 Test facilities

3.2.1 *JetMachining® Centers and nozzles*

Machining tests were conducted using an OMAX JetMachining® Center (JMC), either a Model 2652 or 2626.[1,2] Figure 1a shows the Model 2652 JMC. There is a collection of accessories available for machining special features using AWJs. One of the accessories is the Rotary Axis, a robust waterproof rotary head that allows the waterjet to cut three-dimensional features.[3] Tests of meso-micro machining were conducted using three nozzles: one production nozzle (7/15 Mini

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[1] http://www.omax.com/machine_details.php?product=2652

[2] http://www.omax.com/waterjet-cutting-machines/model-2626.php

[3] http://www.omax.com/accessories-rotary-axis.php

MAXJET5 nozzle) and two experimental nozzles. Typical pump pressures were between 345 to 380 MPa. Abrasives were gravity fed from the hopper via a feed tube connected to the feed port of the nozzle body. Figure 2 illustrates photographs of the 7/15 nozzle which consists of a 0.18 mm ID orifice and a 0.38 mm ID mixing tube. 220-mesh garnet was used as the abrasive with a flow rate of 0.08 kg/min.

3.2.2 Accessories for 3D machining

There are two accessories developed for 3D machining: the Rotary Axis and the A-Jet articulated cutting head. The Rotary Axis is for machining axisymmetrical features on workpieces. The A-Jet, originally developed for making beveled and angle cuts, has been extended for taper compensation and other 3D machining tasks.

Rotary Axis

The Rotary Axis is a robust, waterproof rotary head that allows the waterjet to cut XYZ paths to create complex 3D parts. It is bolted to the frame of the JetMachining Center facilitating submerged operations (Figure 3).

A-Jet

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 (Figure 4). 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.

3.3 CAD/CAM programs

OMAX’s PC-based CAD program, LAYOUT, was used to draw, either from scratch or import from AUTOCAD, specific drawings of patterns to be machined with the nozzles. The patterns were subsequently converted into tool paths according to various parameters pertaining to the workpiece (material types and thickness), the abrasive waterjet (pressure and nozzles), the abrasives (type, mesh, and mass flow rate), and cut qualities (from Q1 through Q5) (Liu et al, 2009). LAYOUT then passes a tool path file to the CAM program, MAKE, for automated machining of the parts. MAKE controls the operations of a suite of hardware accessories such as the Rotary Axis and A-Jet 2D and 3D machining.

4. Results

The processes described Section 3.1 may be divided into two main categories: those that do and those that do not require accessories. 3D parts were machined with the processes by manipulating workpiece either during or after the machining process, and by adding accessories to enable 3D machining. Selected 3D samples are presented in this section to demonstrate the extension of AWJ platforms from 2D to 3D machining. This is one of the technological merits of waterjet technology: multiple dimensional machining that is being taken full advantage of only recently as the emerging technology is maturing.

4.1 AWJ 2D Platform with No Accessory

The processes described in the first five bullets in Section 3.1 can machine 3D parts by employing the AWJ 2D Platform without the need for additional accessories. There are six (6) sub-processes under this category.

Stretching/rearranging of 2D parts

One of the simplest transformations is to stretch or rearrange a 2D part into a 3D one. While testing a relatively long-term cutting performance of a JetMachining Center, we often resort to cutting a spiral piece that takes about 20 minutes to complete. Figures 5a and 5b illustrate the tool path and the AWJ-cut 6.4 mm thick aluminum spiral (anodized), respectively. By supporting the spiral at its center, the gravity acts on the spiral and immediately turns it into a 3D counterpart, as illustrated in Figure 5c. Note that the center support is another AWJ-cut 3D part to be described in a subsequent section.

AWJ Etching

AWJ etching uses the brightness values in electronic images as a means of dictating a height map, the values of which can then be converted into a speed gradient. The speeds from the gradient are then assigned to the corresponding brightness values within the image. The utility then produces a stream of fine motion commands with tightly controlled velocity, referred to henceforth as a 'bitstream'. In turn, the bitstream-processing controller software can process the bitstream that was created and move the abrasive waterjet nozzle fast or slow over a given area as directed by the path. The result exhibits three-dimensional characteristics. The etching process is accomplished all in one path, without the need to separate into multiple paths that have different etching speeds. Figure 6 illustrates a dragon etched on an aluminum block (Webers, et al., 2010).

Cutting parts multiple times

A 3D part made with this process involves cutting the part multiple times. The orientation of the part changes for each additional cut. Figure 7 illustrates one-half of a surgical clamp that was cut on a 9 mm OD stainless steel rod. Three steps were used to cut the clamp as illustrated in the photo sequence from left to right in Figure 7. First, the overall shape of the clamp was cut. The left photo shows the result of the initial cut by rotating the part 90 degrees from the cut plane (left). The part was then trimmed to remove any excess material by rotating the part 90 degrees from the initial cut plane (middle). Finally, the grooves on the clamp were cut by rotating the part another 90 degrees (right). The matching half of the clamp was cut by applying the same three steps, with a different curvature. Note that all the rotations were conducted manually.

Secondary process

For some applications, the AWJ-cut 2D part needs a secondary process to carry out the 3D transformation. Figure 8 illustrates a carbon fiber knee brace. Initially, AWJ was employed to cut its components into a 2D shape. Heat was applied to soften the 2D components and they were then bent into their final 3D shape.

Unfolding followed by folding

For a certain type of 3D parts, they could be unfolded first into 2D components, with the use of unfolding software such as Rhinoceros. The 2D components are then cut with the AWJ 2D platform and then refolded back to the original 3D parts. Figure 9a illustrates a conical funnel and its unfolded counterpart using the Rhinoceros software (Version 4.0). The unfolded drawings were imported into the OMAX LAYOUT/MAKE PC-based CAD/CAM program to cut the unfolded 2D pieces. These pieces were then folded into the funnel shape, as shown in Figure 9b.

Layer Manufacturing

Basically, an AWJ layer manufacturing system consists of a combination of a CAD system and an operation machine to perform the fabrication of a layer under computer control. First, a 3D CAD representation of the part is created by a computer software package such as Solidworks, Rhinoceros, or AutoCAD. The computer representation of the part is then sliced into layers of a certain thickness, and the two-dimensional profile on all the layers are converted into tool paths to be cut via AWJ. The part then is reassembled layer by layer. The laminated object manufacturing (LOM) is another form of layer manufacturing. It produces parts by assembling and bonding layers of material cut to the desired shape to form a laminated structure.

Figure 10a illustrates the manufacturing steps to produce a microchannel system formed by diffusion bonding of a stack of slotted and blank titanium shims. The slotted shims were machined by AWJ, as shown in Figure 9b. The diffusion bonded stack of a microchannel system is shown in Figure 10c. Figure 10d illustrates the end view of the microchannels after the two ends of diffusion bonded microchannel system are cut away.

Layer manufacturing is most suitable for fabricating parts with complex internal features that are difficult to machine otherwise. The use of the A-Jet facilitates the machining of such features. By slicing the part into many layers, it can be fabricated by stacking the layers together. Layer manufacturing is often used in rapid prototyping to take advantage of its flexibility and fast turnaround.

4.2 *2D AWJ platform with accessories*

The process described in the last bullet of Section 3.1 requires additional accessories. The two accessories mounted on the 2D AWJ platform for machining 3D parts are the Rotary Axis and A-Jet described in Section 3.2.2. All the processes described Section 4.1 still apply. The features machined with these accessories, however, are considerably more complex than those of others described in Section 4.1.

Rotary Axis

The Rotary Axis as illustrated in Figure 3 is used to machine many axisymmetric and 3D features on tubes, pipes, and other cylindrical parts. Figure 11 illustrates two model Space Needles cut on an acrylic and aluminum cylinders, respectively (Liu and Schubert, 2012). Figure 12 illustrates a set of copper tubes on which high-aspect-ratio slots were cut with an miniature AWJ nozzle (0.13 mm ID orifice and 0.25 mm ID mixing tube) currently under beta testing (Liu et al., 2011). These parts, which are very difficult if not impossible to cut with either laser or EDM, serve as the stator and rotor of high-efficiency small motors/generators (Trimble, 2011). The Rotary Axis was also used to cut interlocking links from a rigid titanium tube, as illustrated in Figure 13 (Liu, et al., 2011).

The advancement of AWJ 3D precision machining, there is considerable potential for applying waterjet technology to machining biomedical, microelectronic, and aerospace components. Figure 14 illustrates a titanium mesh cage for orthopedic applications. The titanium mesh cage (middle) was machined with a beta miniature AWJ nozzle (0.13 mm ID orifice and 0.25 mm ID mixing tube). A titanium tube with an OD of 6 mm and a wall thickness of 0.5 mm was mounted on the Rotary Axis. A stainless steel rod (left) was inserted into the tube as a sacrificial piece to prevent damage of the opposite wall from the spent AWJ. The spent AWJ continues cutting into the sacrificial rod and dissipates its energy inside the rod, as shown in the figure. It is important to make sure that the rod is only partially cut through such that the opposite side of the titanium tube is protected. Also shown is the unfolded 2D diamond shaped holes (right) cut on a thin stainless steel sheet.

Although AWJ etching described in Section 4.1 is a form of milling, it is unable to control the milling depth precisely. By mounting a workpiece on the end of a rotary platform, with the waterjet impinging onto the surface perpendicular to the axis of rotation, milling with good depth control can be carried out. The depth of milling is proportional to the dwell time of the waterjet workpiece on a spot of the workpiece. Therefore, a smooth milled surface would require the workpiece rotating at very high speeds. Milling of near-net-shaped optical surfaces was performed by mounting the workpiece on a precision air spindle with a rotating speed of 10,000 rpm (Liu, 1998). An abrasive slurry jet (ASJ) operating at about 60 MPa was used to machine a convex surface on a float glass (Figure 15) and a concave surface on an aluminum nitride ceramic (Figure 16).

A-Jet

The A-Jet is the key to 5-axis waterjet cutting. In addition to a machine's X, Y and Z axes, the A-Jet provides two tilt angles – one perpendicular to the X axis and the other perpendicular to the Y axis. The A-Jet works within the safety limitations of abrasive waterjet cutting (Olsen, 2012)). While there are five axes of motion, the range of the two tilt axes is controlled to a specific limited distance so that the abrasive waterjet stream is always shooting in a generally downward direction toward a machine's water tank. OMAX's A-Jet articulating head, for instance, tilts at any angle within its "120-degree cone of safety."

The A-Jet can also be used to compensate for the natural taper that occurs with a waterjet stream. The incorporation of the A-Jet onto a 2D AWJ platform, either a JetMachining Center or a MAXIEM JetCutting Center, enables beveling parts for welding preparation and mitering cuts for parts that intersect at an angle. Figure 17 shows an example of a beveled cut on an aluminum block. The beveling operation is commonly used as a welding preparation. Figures 18a and 18b illustrate two OMAX logos with bevel cuts on a stainless steel plate and a titanium honeycomb, respectively. The A-Jet is also often used to cut countersinks.

Pairing of Rotary Axis and A-Jet Combination

The pairing of the Rotary Axis and the A-Jet facilitates machining of a variety of complex 3D features on tubes, pipes, and other cylindrical parts. Figure 19a illustrates the setup of the two accessories for cutting intricate patterns on a stainless steel tube (Figure 19b). Another example is to cut fish-mouth shapes and other end shapes necessary to join tubes or pipes to one another, as illustrated in Figure 20.

Role of Software

The A-Jet and Rotary Axis provided the machine motion necessary for 3D AWJ machining, but improvements in machine programming really advanced the cutting capability. OMAX, for instance, developed the latest version of its Intelli-MAX Software Suite specifically to support multiple-axis coordinated machine motion and 3D part processing. With this software, fabricating shops can quickly and easily program and cut 3D patterns in a multitude of applications, from the peripheries of tubes and pipes to fitting operations to prep cuts and bevels.

To make 5-axis programming even easier, the Intelli-MAX software links into other common CAD/CAM systems. This allows shops to program parts in software packages that most fabricating shops are already comfortable with and using. The program files are then translated within OMAX's software for machine movement.

The ease of retrofitting existing 2D machines with the A-Jet, Rotary Axis, and innovative software functions has made 3D cutting easy and attainable. While technology advancements have simplified 5-axis cutting, there are certain workpiece factors that must be considered when using AWJ cutting.

Figure 21 illustrates a bevel part cut with the A-Jet. Without software control, programming that part with multiple sharp angles and bevels would have taken a long time. With the advanced machine control software, the programming job has been made easy by simply taking the CAD file and creating the cutting path in seconds.

5. **Summary and future work**

5.1 Summary

Although AWJ technology is amenable to 3D machining, there are only limited 3D AWJ systems commercially available for 3D machining. One of the reasons pertains to inadequate capturing of the spent abrasives in a 3D environment to mitigate damage to the target workpiece or potential hazards to operators. Most AWJ systems are therefore designed for 2D machining with the spent AWJ directing generally downward to the water tank below. This paper describes several approaches to take advantage the 3D machining capability of AWJ by expanding the capability of 2D AWJ platforms to 3D machining. There are generally two approaches to machine 3D parts using a 2D AWJ platform; one approach does not require accessories, and the other does require accessories. For the approach that requires no accessory, either additional cuts at different orientations of the same workpiece or a secondary process will be performed. For the approach that requires accessories, 3D parts will be machined by a single or multiple cuts.

Machining processes based on the two approaches, as described in Section 3.1, were applied to cut sample parts to demonstrate the versatility of AWJ technology for machining 3D parts made of a variety of materials with a wide range of sizes from macro to micro scales. The multi-dimensional machining capabilities, together with the technological and manufacturing merits listed in the introduction, present considerable potential for the emerging AWJ technology to fabricate high-value-added components for aerospace, electronic, energy production, and biomedical applications.

5.2 Future Work

In order to take advantage of the 3D capability of AWJ while operating the machine within the limitation of safety (Olsen, 2012), we will continue developing novel approaches to enable 3D machining using a 2D AWJ platform. For example, several processes described in this paper can undergo further innovation for machining intricate 3D parts. With the newly introduced MicroMachining Center, one of the emphases will be to enable 3D micromachining by incorporating the processes described in this paper.

Acknowledgment

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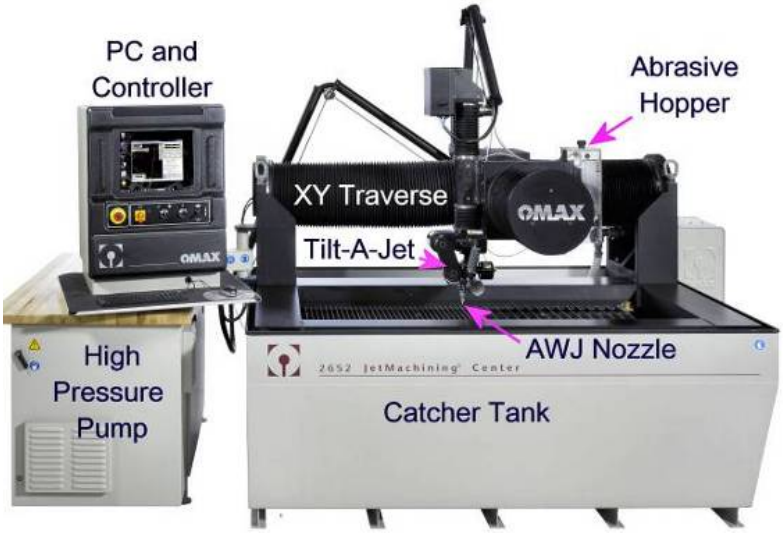


Figure 1. Model 2652 JetMachining Center

Figure 2. 7/15 nozzle

Figure 3. Submersible Rotary Axis

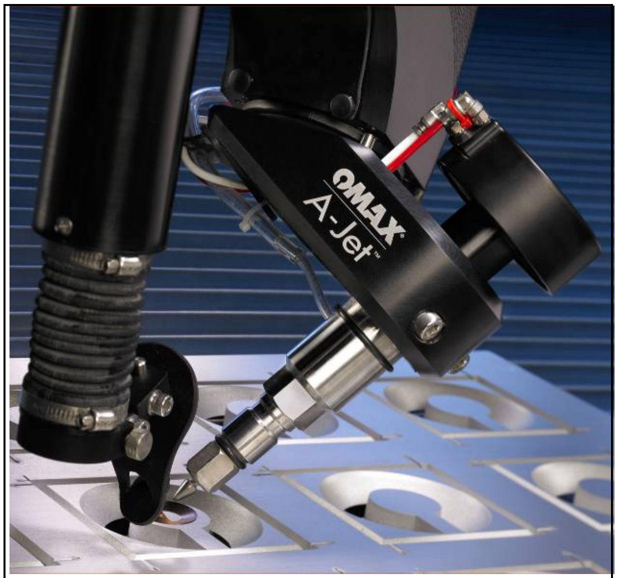
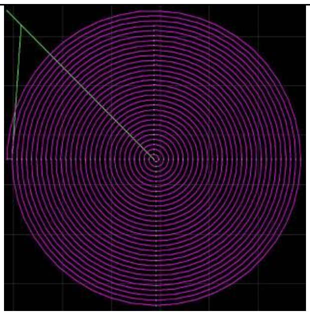
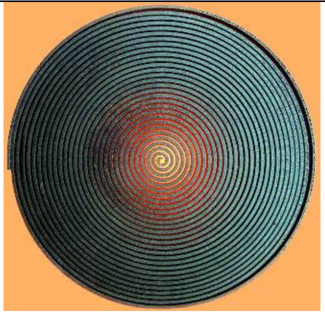


Figure 4. A-Jet



a. Tool path of spiral - quality level 3



b. AWJ-cut aluminum spiral (0.13 mm thick)

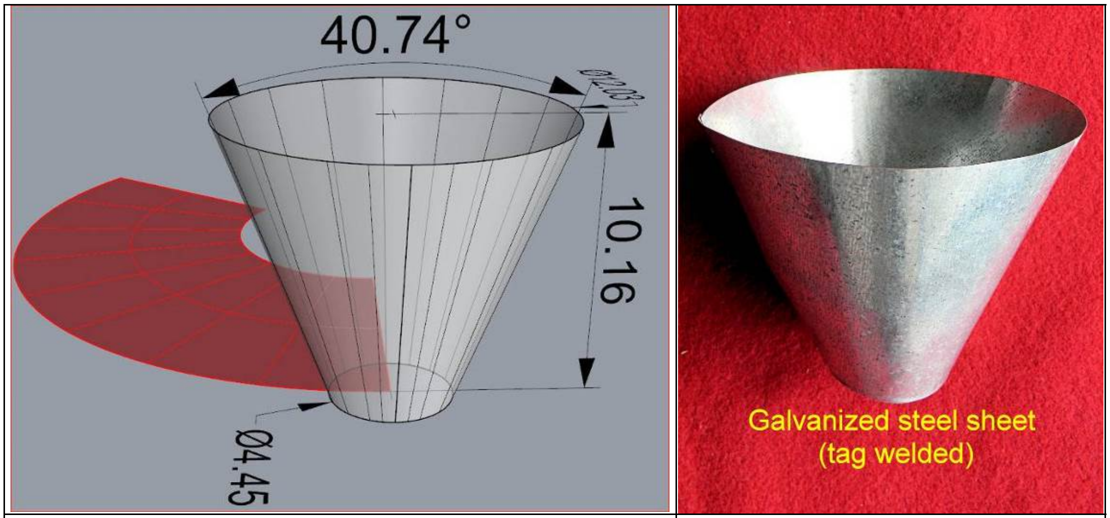
c. Stretching of spiral with added weight

Figure 5. Transformation of a 2D spiral into a 3D counterpart via stretching

Figure 6. AWJ etching on an aluminum plate (Webers et al., 2010)

Figure 7. Surgical Clip

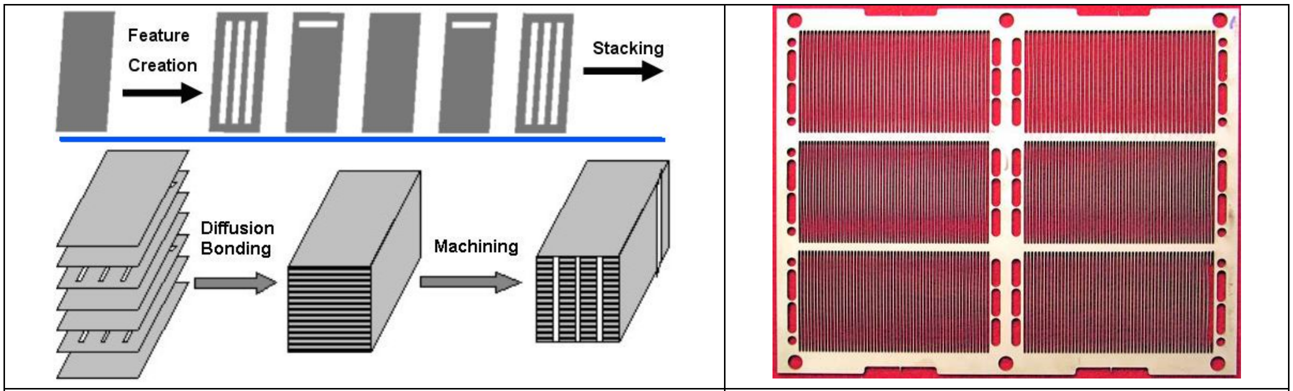
Figure 8. Carbon fiber Knee Brace



a. 41-deg funnel and unfolded surface (unit: cm)

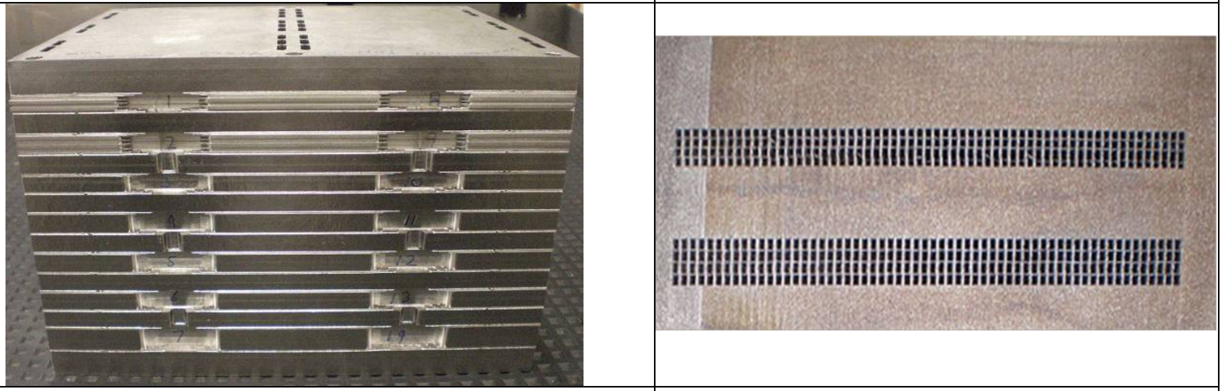
b. Refolded funnel

Figure 9. Unfolding and refolding a 40.7-deg funnel



a. Process for microchannels (Tonkovich et al., 2005)

b. AWJ-cut titanium slotted shim



c. Diffusion bonded microchannels system (courtesy of PNNL)

d. Completed microchannels (courtesy of PNNL)

Figure 10. Diffusion bonding of slotted and blank shims to form microchannels

Figure 11. Space needles

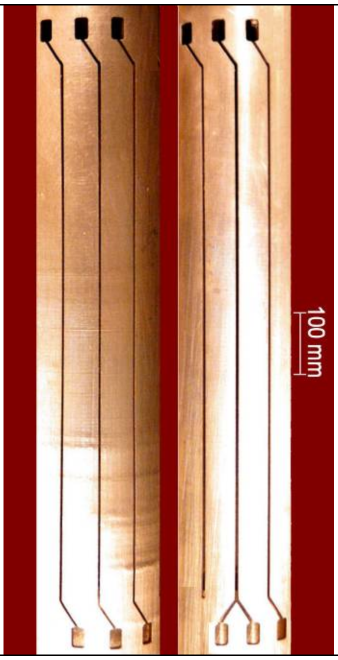


Figure 12. Slotted copper tubes

Figure 13. Ti interlocking link

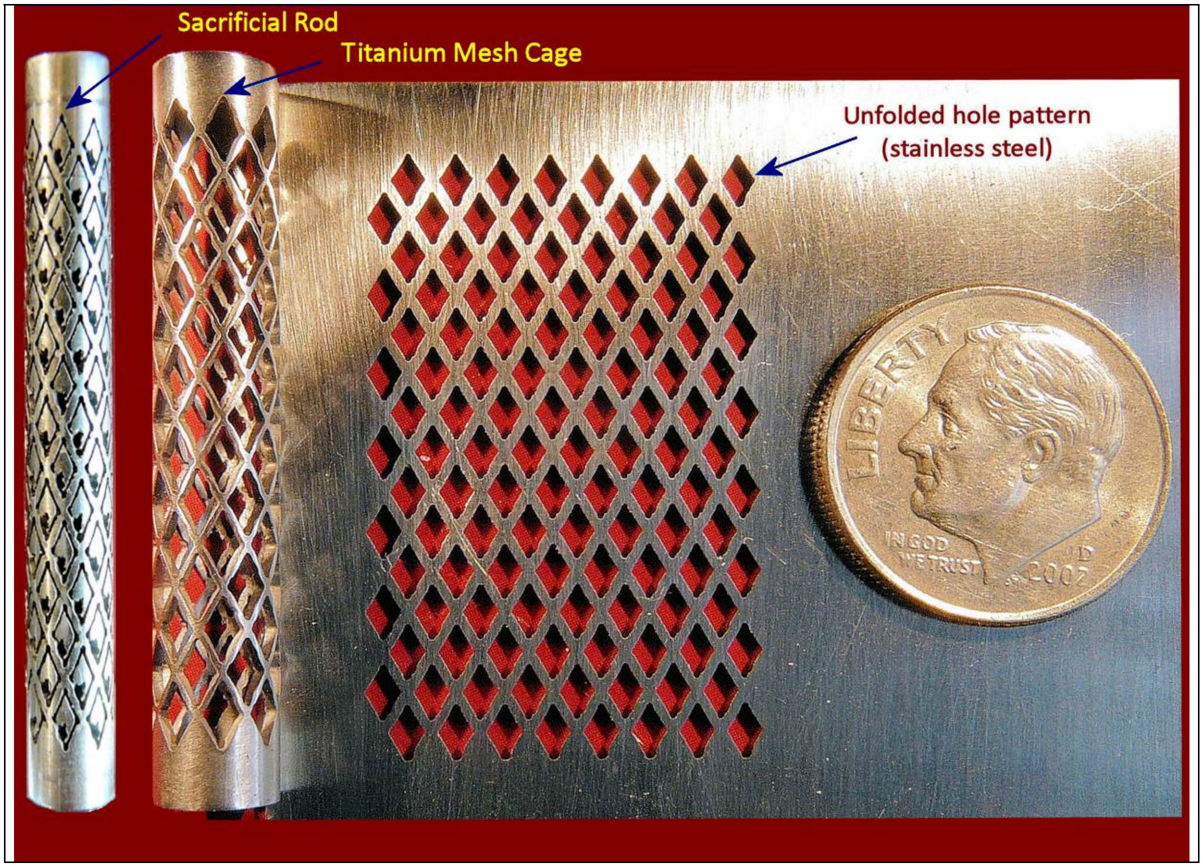


Figure 14. Orthopedic titanium mesh cage, and sacrificial its unfolded shaped holes

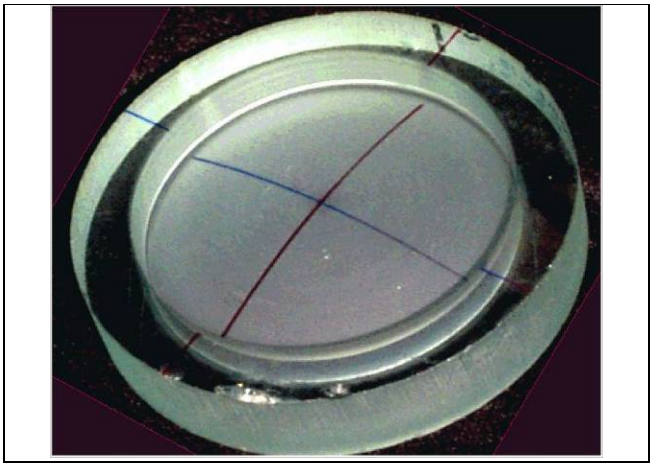


Figure 15. Near-net-shaped glass lens

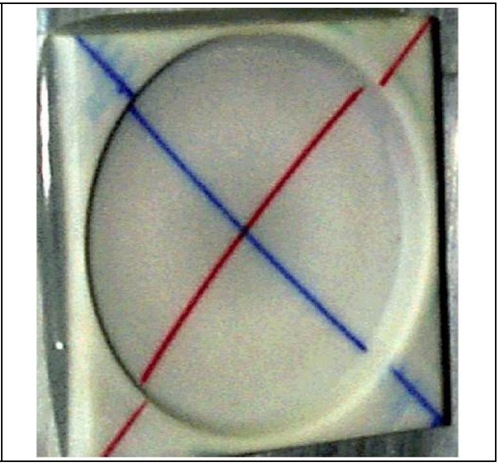
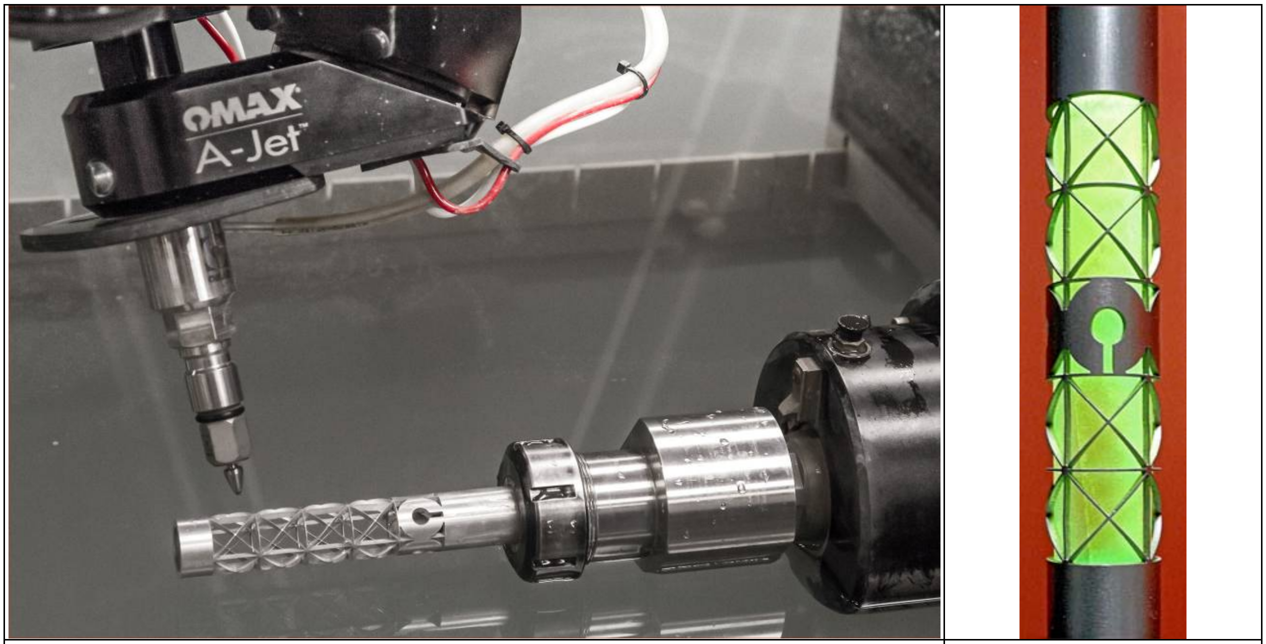


Figure 16. Near-net-shaped AlN lens

Figure 17. Bevel cuts on aluminum block using A-Jet

Figure 18. OMAX logos with bevel edges cut with A-Jet



a. Pairing of Rotary Axis and A-Jet

b. Intricate 3D features

Figure 19. Intricate 3D features machined with pairing of Rotary Axis and A-Jet

Figure 20. Fish-mouth end bevel of Steel Pipe

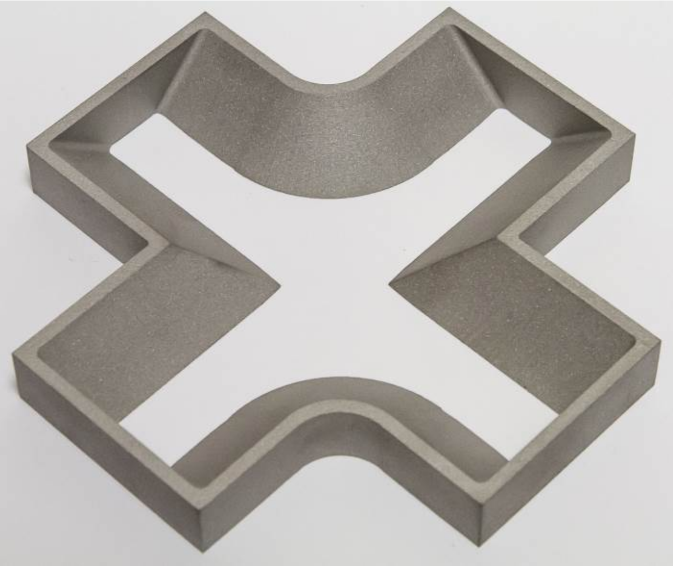


Figure 21. Software controlled bevel cut