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Paper

THE STATE-OF-THE-ART OF PRECISION ABRASIVE WATERJET CUTTING

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ABSTRACT

Abrasive waterjet cutting has become a main stream machining technology in today's manufacturing world. This paper will serve as an overall review of the state-of-the-art of this technology applied to precision machining. Topics will cover the cutting process, hardware (pumps and XY tables), and software, as well as the latest tilting head technology for taper removal.

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1. INTRODUCTION

Fifteen or 20 years ago abrasive jet was the technology of last resort for severing difficult materials that could be cut no other way. These units were crude, noisy, and dirty. A nozzle was hung on an X-Y burning table and the resulting tolerances and surface finish were comparable to a burning operation, only slower. Operating these machines was almost an art form, a special skill by which experienced operators could make good parts while others could not. Few machine shops wanted one, and most abrasive jet cutting was done by specialty shops.

Today, things are different. Modern abrasive jet machines can hold tolerances of +/- 0.005 inch (0.127 mm) or better. Noise and flying dirt can be minimized by underwater cutting. Abrasive jets still are useful for machining difficult materials such as INCONEL® alloys, titanium, and composites, but they are most widely used for easily cut materials such as mild steel and aluminum. Today abrasive jets are being placed in machine and fabrication shops alongside traditional machinery and operated by relatively unskilled labor. They are used for one-of-a-kind through medium-volume production. This paper will give a state-of-the-art review of this technology.

Figure 1 shows a typical layout of an abrasive waterjet machine. Several topics involving the process, high pressure pumps, cutting table, and the software will be discussed in details.

Figure 1 A typical layout of an abrasive waterjet machine

2. PROCESS

2.1 Working Principles

The workings of an abrasive jet nozzle are shown in Figure 2. Clean water at pressures up to 55,000 PSI (380 MPa) is routed to a chamber directly above a sapphire orifice. The water accelerates through the orifice, forming a jet about 0.014 inch (0.36 mm) wide that is centered within a carbide tube 0.030 to 0.040 inch (0.76 to 1.02 mm) wide.
Abrasives enter the low-pressure region above the tube and are accelerated by the jet to form a high-speed slurry at the bottom of the tube. This slurry is the cutting tool. The cutting process is like grinding, except that abrasives are moved through the material by water rather than by a solid wheel. The process is a combination of rapid erosion and rapid cooling.

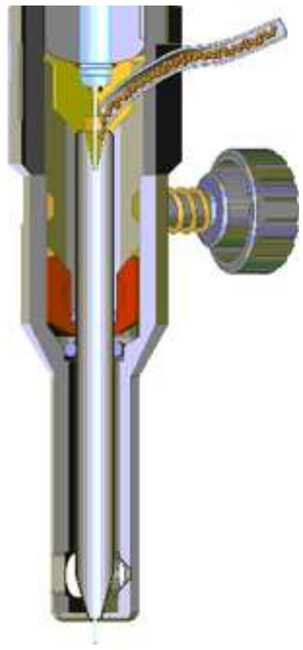


Figure 2
The architecture of an abrasive jet

The abrasives used in the cutting also wear away the carbide tube. The first abrasive jet nozzles wore down so quickly that the jet would change its characteristics during production of a single large part. This made it impossible to hold tolerances. Early abrasive jets could be used only when subsequent machining could be performed or for very crude work. New materials have increased tube life from as short as three or four hours to 50 or 100 hours.

The jet itself is moved by an X-Y mechanism over a table that supports the work piece. Pump power usually ranges from 20 to 100 HP, and table sizes are 2 square feet (0.185 m^2) and larger. Setup time on waterjet systems is rapid. With this type of cutting, all shapes are made with a single tool, and no multitool qualification is required. Cutting forces are low, so minimal fixturing and clamping are required. The process is effective for short runs and one-of-a-kind prototype parts, as well as for high-volume production.

2.2 Cutting Speed

The cut surface can range from a smooth sandblasted appearance to a rough, striated surface, depending on the speed at which the jet moves through the material.

At higher speeds, the jet wiggles from side to side within the cut, with greatest amplitude at the bottom of the cut. The cutting speed for a material usually is expressed in terms of the speed at which the jet can just barely sever the material. Then parts are made at various fractions of this speed, depending on the surface quality required (see Figure 3).

Another complication is that the exit point of the jet on the bottom of the material lags the entry point on the top of the material. This situation produces errors when the jet executes a corner or tight radius. For straight-line cutting, the speed is limited by the side-to-side motion of the jet; for shape cutting, it is limited by the lag of the jet. With modern controllers, software handles these complications, and the only effect is that it takes longer to make a complex part than a straight cut of equal length.

Newcomers to abrasive jets often ask, "How fast can I cut this material?" intending to compare the process with something they know, such as oxyacetylene burning or sawing. As we have seen, the answer to this question is complicated and depends even on the shape being cut. The cutting speed is given by the equation below [1]:

$$V = \left(\frac{fa \cdot M \cdot P^{1.594} \cdot d^{1.374} \cdot Ma^{0.343}}{788 Q \cdot H \cdot Dm^{0.618}}\right)^{1.15}$$

Where: P = Stagnation pressure of the water jet in MPa, typically 345; d = Orifice diameter in mm, typically 0.36; Ma = Abrasive flow rate in g/min. typically 363; fa = Abrasive factor (1.0 for garnet); Q = Quality seen in Figure 3. Set Q equal to 1.0 to calculate separation speed; H = Material thickness in mm; Dm = Mixing tube diameter in mm, typically 0.76 to 1.02; V = Traverse speed in mm/min; M = Machinability of material (see Table 1).

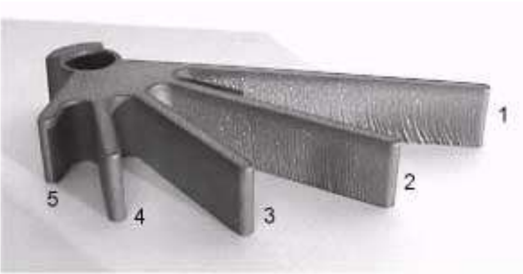


Figure 3 Five fingers cut in equal times show effect of quality settings (1-5)

Table 1. Machinability, M

Hardened Tool Steel 80
Mild Steel 87
Copper 110
Titanium 115
Aluminum 213
Granite 322
Plexiglas™ 690
Pine Wood 2,637

Real parts will be made at 10 percent to 50 percent of the separation speed, depending on the surface finish and corner qualities required. Note that as the thickness is doubled, the cutting speed is more than halved. In general, this means that stacking is not a good idea, because making a single part takes less than half the time of cutting a double thickness. However, for thin parts, the process may be limited by the top speed of the machine, and stacking can be effective up to a height of about 0.25 inches (6.4 mm).

2.3 Considerations in Part Design

The jet diameter is from 0.020 to 0.050 in. (0.5 to 1.27 mm), giving a minimum part feature radius of half that amount. Very thin sections can be made, but the jet is not good at making skim cuts in which less than one jet diameter is to be removed. It also is difficult to make interrupted cuts such as those required for cutting both sides of a tube. When you are cutting one side of a tube, you will need a jet deflector to prevent damage to the other side.

Depth control is not good for making cuts that go only partway through the material. The best that can be expected is about +/- 20 percent of the depth being cut. You can make decorative grooves that do not sever the part, but precise depth control is not possible.

Even with these limitations, there are a variety of design options. For instance, square and rectangular holes can be made to match with tabs on the mating part. This allows a self-jigging assembly that requires less labor to assemble and increases precision. The tab then can be twisted, plug-welded, or drilled and tapped to make permanent or temporary assemblies.

With abrasive jet machining, it is possible to harden the material first and then cut the part. Springs and flexures can be made directly from heat-treated steel. However, residual stress can affect part accuracy because a partially cut workpiece may break the balance of residual stresses and cause the part to deform and thus deviate from the original tool path.

2.4 Precision

Precision depends on the machine, the nozzle condition, and the cutting process. In a precision machine with a perfect nozzle, the major errors come from the cutting process. The cutting process produces a slightly tapered angle in the kerf and, therefore, on the cut edge. Surprisingly, the taper angle is greatest in thin materials. A steel part 2 in. (50 mm) thick may have only a 0.001. to 0.003-in. (0.025 to 0.076 mm) taper, while a 1/8-in. (3.2 mm)-thick part may have a 0.005- to 0.008- in. (0.127 – 0.203 mm) taper. Five-axis machines can remove this taper with software, which will be the topic for section 6.

As the nozzle wears, the stream diameter becomes larger, and the tool offset must be increased to compensate. This introduces the possibility of measurement and operator error. A very old nozzle may produce an elliptical stream for which you cannot compensate.

Precision errors may occur at lead-in and lead-out points, where a small projection or indentation may appear on the surface of the part. Generally, these errors are small and the lead-in can be placed at some unimportant portion of the part. For holes, the lead-in errors can be removed completely by tapping or reaming the hole. Holes can be made precisely enough to tap without secondary operations.

2.5 Environment and Safety

An exposed jet is noisy and throws a lot of abrasive dust. These factors are eliminated by cutting underwater. An abrasive jet machine cutting under water can be placed anywhere that you might place a grinder. No noxious fumes or smoke is generated, and the part does not become contaminated with cutting oils.

The machine generates two waste streams -- excess water containing very small amounts of solid fines, which usually is sent directly to a drain, and spent abrasives with metal slugs, which are sent to a landfill. If the material being cut is poisonous -- lead or beryllium, for example -- both waste streams must be cleaned or recycled.

2.6 Operating Costs and Maintenance

An abrasive jet machine costs about $25 (USD) per hour to operate for consumables and maintenance parts. Cutting rates can be estimated from the equation given previously and. of course, vary with material and thickness. For example, ½-in. (13 mm) thick stainless steel cuts at about 6 IPM (152 mm/min) with a good-quality edge. This translates to a cost of about 7 cents per inch ($2.76/m). It would cost about $.70 to cut out a 3-in.(7.62 cm)-diameter disk or to form 10 holes with 5/16-in.(0.79 cm) diameter.

The higher the pressure, the faster the cutting and the more maintenance required. At pressures around 60,000 PSI (414 MPa) maintenance costs skyrocket because these pressures cause stresses that exceed the endurance limits of the steels used for pressure containment. For this reason, jet cutting machines usually operate at 55,000 PSI (380 MPa) or less. But even at these lower pressures, jet cutting machinery requires more maintenance than traditional machine tools. Operators tend to choose higher-pressure operation for the productivity gain and then live with the higher maintenance.

Maintenance items include all parts wetted by the high-pressure water and parts through which abrasive flows. Nozzle parts are replaced at 50- to 100-hour intervals, and pump seals are replaced at 300- to 1,000-hour intervals. New troubleshooting and maintenance techniques must be learned for successful operation of abrasive jet equipment, but the skills to be learned are not difficult, and thousands of successful machines are in operation.

2.7 Typical Applications

Consider using an abrasive jet when

- Making flat parts ranging from shim stock to 2 in.(50 mm) thick.
- Weld quality requires slag removal from thermal cutting processes.
- Production quantities are low, so quick setup time is important.
- Taps or other tools for secondary operations are damaged by thermally hardened edges.
- Precision parts would reduce or eliminate secondary operations.

- Self-jigging parts would reduce weld setup time.
- Machining copper, glass, or other materials not easily workable by other processes.

3. PUMPS

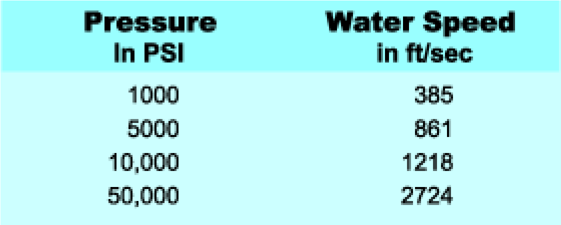
3.1 Pump Types

Table 2 shows the speed at which water flows from a nozzle at various upstream pressures as calculated by using Bernoulli's equation. The table also can be used as a rough guide to determine how fast water would have to be moved by an impeller to develop desirable pump pressure.

A speed of about 385 ft/s (117 m/s) would be required to develop even a modest pressure of 1,000 PSI (6.9 MPa). This would equate to an RPM of 14,700 in a 6-in.(15.24 cm)-dia. impeller pump. Because of the impractically high RPM required of a high-pressure impeller pump and the associated frictional losses, all high-pressure pumps are positive displacement pumps.

Among the positive displacement pumps are gear pumps, vane pumps, screw pumps, and plunger pumps. The first three rely upon close tolerance gaps to limit leakage from the high-pressure to the low-pressure regions. When pumping a viscous liquid, like oil, pressures up to 10,000 PSI (69 MPa) are possible. However, for water, even small clearances allow significant leakage, and pressures above about 1,000 PSI are impractical for all but plunger pumps in which a positive seal is present.

Table 2. The relationship between pressure and water speed



Pressure in PSI	Water Speed in ft/sec
1000	385
5000	861
10,000	1218
50,000	2724

3.2 High-Pressure Plunger Pumps

All water pumps for pressures above 10,000 PSI are plunger pumps. A solid plunger is pushed into a closed chamber, raising the pressure and expelling the pumped fluid through an outlet check valve. Then, the direction of the plunger motion is reversed, and low-pressure fluid fills the chamber through an inlet check valve. The continuously reciprocating plunger provides the pumping action (see Figure 4). Two popular drive types for moving the plunger are currently available. The crank pump moves the plunger with a crank similar to the one in an automobile engine. The intensifier pump drives the plunger with a hydraulic cylinder that usually is operated with oil.

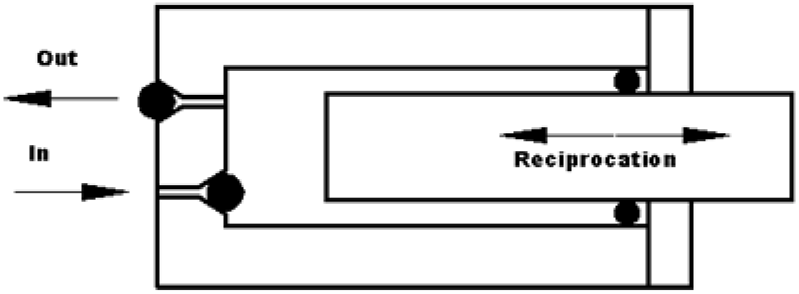


Figure 4 Diagram of a plunger pump

Before examining the two drive types, consider what happens in the pumping chamber illustrated in Figure 4. At high pressures, the pumped liquid is compressible. At 55,000 PSI (380 MPa), water is about 12 percent compressible. That means that the plunger must move enough to fill 12 percent of the chamber volume before the pressure reaches 55,000 PSI. At that point the outlet check valve can open against the pressure already in the output line. Then, at the end of the stroke, when the plunger reverses and the outlet check valve closes, any water trapped in the cylinder continues to expand and push on the plunger until the plunger has moved far enough to drop the pressure on the inlet check valve. The energy put into the plunger motion by this expanding trapped water can be recovered or not, depending upon the drive type.

3.3 Drive Types

In the crank pump this expansion energy is recovered in the same way that it is recovered from the expanding hot gasses in an internal combustion engine. It goes back into the kinetic energy of the rotating components.

In the intensifier pump, the energy is dumped into the oil of the hydraulic circuit, causing heating. For this reason, intensifiers operate at an efficiency of 60 to 70 percent, whereas crank drive pumps operate at 86 percent [2]. The heat dumped into the oil of an intensifier drive must then be removed-usually by an oil-to-water heat exchanger. This requires extra water for cooling purposes and significantly higher electric costs to pay for the wasted energy.

Other differences between the two pump types arise from the relative operating speeds of the plunger. Crank plunger speeds are about 30 IPS (76 cm/s) while intensifier plunger speeds are usually about 6 IPS (15 cm/s). For comparable output flows, the intensifier plungers, cylinders, and check valves must be larger and therefore more expensive than the corresponding crank drive parts. Also, a crank is much less costly and complex than a hydraulic system. Both the initial costs and part maintenance costs are lower for the crank drive pump.

3.4 Why Two Drive Types?

Why are there two types of pump drives in the marketplace? Here, a little history is helpful. Through the 70s and 80s, crank drive pumps held almost the entire market for pressures 20,000 PSI (138 MPa) and below, because of their low-cost reliable operation. Intensifier pumps were used for 30,000 PSI (207 MPa) and greater for the reasons that follow. Early pumps were plagued by three problems that favored the slow operations of intensifiers at the higher pressures: metal fatigue, check valve wear, and seal life.

Metal fatigue is the failure of metals due to repeated loading and unloading, causing the initiation and propagation of cracks. Component life depends on the materials used, the stress levels in operation, and the number of load cycles applied. Steels have a stress level below which they will never fail no matter how many load cycles are applied. Usually, a stress level just below that which causes failure at 10,000,000 cycles will never cause failure. An intensifier achieves 10,000,000 cycles in about 3,000 hours and a crank drive pump in about 300 hours. Both can be designed for infinite fatigue life at pressures below 55,000 PSI (380 MPa) using modern materials and stress control techniques. Fatigue is no longer an issue limiting crank pumps.

Check valve wear is another problem solved by modern technology. Metal seats wear by adhesive wear, when particles transfer from one surface to another. Wear life depends upon the number of open and close cycles and the operating pressure. Modern ceramics have the strength necessary for check valve components, and adhesive wear between metal and ceramics is so low that check valve life is no longer a concern on crank drive pumps.

Seal life is what currently limits crank drive pumps to pressures of about 55,000 PSI, and it is advances in this area that have allowed the pressure range of crank drive pumps to rise. Dynamic seal life is dependent almost entirely on the total length of travel and surface finish of the plungers. When pumping a gallon of water, the dual plungers in an intensifier might travel about 200 in. (5 m) each, whereas the three plungers in a crank drive would travel about 1,000 in. (25 m) each. If each pump has the same plunger-seal technology, the intensifier seal would last five times as long. Differences between 300 hours and 1,500 hours could be seen.

In addition to these formerly dominating issues, there are other points of comparison. Because of the low plunger speed, the intensifier delivers one or two large discharges per second, whereas the crank pump delivers 30 small discharges per second. The pressure output of the crank pump is very smooth, and the system does not require an accumulator to smooth the pressure output. No marks are left on the part because of pressure ripple with a crank drive pump, nor is there any large high pressure vessel that can cause a safety concern as with an intensifier pump.

Even with the accumulator, the pressure dips about 2,000 to 5,000 PSI (14 to 35 MPa) at each shift of the intensifier. For comparable cutting quality, the intensifier must run at a pressure 2,000 to 5,000 PSI greater than the crank drive to maintain quality at the dip.

The two pumps have nearly comparable pressure control. The intensifier output pressure is controlled by stroke variation and the hydraulic pump flow. Varying the RPM of the electric motor through a variable speed drive controls the crank drive output pressure.

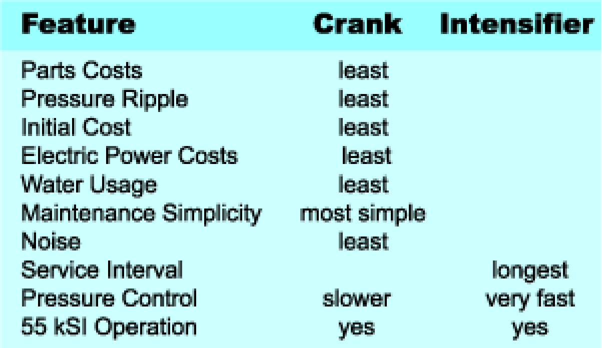
The intensifier-accumulator combination responds quickly to load changes and can be used to run independent nozzles turned on and off at random, while maintaining a constant pressure level. The crank drive can run multiple nozzles, but for quick response, dump valves must be opened as the nozzles are shut.

The crank operating at about 600 RPM generates far less noise than the hydraulic system of an intensifier. Quiet intensifier pumps are possible only by providing costly sound control measures.

When service is called for, there are many mechanics who understand and can work on crank drive pumps because of the simplicity and close similarity with automobile and other internal combustion engines. Technicians familiar with hydraulic pumps, valves, filters, pressure controls, and heat exchangers are rare and unlikely to be found in the ordinary machine shop.

The main reason for putting up with the low-efficiency, noise, cost, and pressure ripple effect of an intensifier system is to have the increased seal life that goes with low plunger speeds. The intensifier is the pump of choice for a 24-hour operation that runs for weeks without any chance of maintenance. If once-a-month maintenance is possible, the crank drive pump is preferable. At a cost of $0.13 per kW-hr., the electric power cost savings alone pay for a seal rebuild kit each 300 operating hours. A feature comparison between the two pump types is presented in Table 3.

Table 3. Comparison of crank and intensifier pumps



Feature	Crank	Intensifier
Parts Costs	least	
Pressure Ripple	least	
Initial Cost	least	
Electric Power Costs	least	
Water Usage	least	
Maintenance Simplicity	most simple	
Noise	least	
Service Interval		longest
Pressure Control	slower	very fast
55 kSI Operation	yes	yes

4. TABLES

4.1 Table Size

Standard tables from 2 feet square (0.185 m^2) up to 6 by 12 ft. (1.8 by 3.6 m) are available, and custom tables of any size imaginable can be special-ordered from many manufacturers. Custom five-axis machines also are available for use in a variety of jet machining applications. Standard machines, basically XY tables, usually are used to cut parts from flat stock. This section discusses these standard tables.

Table size sometimes is dictated by the parts being produced. Large parts need a large table. However, when making smaller parts, several factors should be considered to determine table size. If a whole sheet of material is to be cut into small parts, a table large enough to fit the stock size may be the best bet, but maybe not. On one hand, nesting on a single large sheet often can save material; on the other hand, loading and unloading a large machine is more difficult because of material weight and the operator's limited ability to reach across a large table.

If small batches of small parts from different materials (a task for which abrasive jets are particularly adept) are to be produced, it is not desirable to spend time loading and unloading partially cut, large sheets. A small table using stock sheared into ½, ¼, or 1/8 sheet may be the most economic solution.

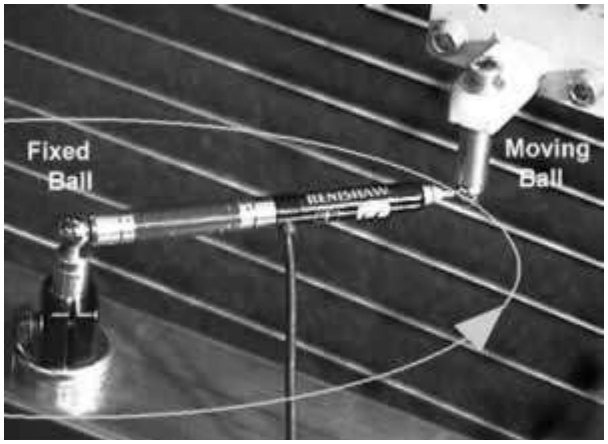
For a shop with high production volume, a table large enough to fit two workstations may be preferable, so that one area can be loaded and unloaded while the other is cutting. A manufacturer may choose a table sized for its part or stock size without fear that a surprise big part will be needed.

4.2 Table Precision

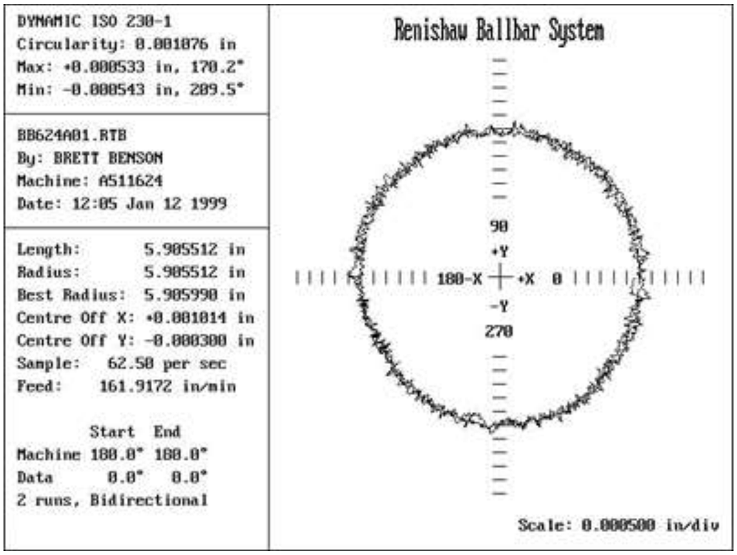
No customer complains about consistent, precise parts. A job shop can service the widest range of customers with a high-precision table. High-precision tables can reduce or eliminate the need for secondary machining operations and lower total part cost. A manufacturer with a specific part or class of parts in mind may find the lower-cost, non-precision table to be sufficient.

Manufacturers document the precision of their tables by several means. The ball bar test is one of the most relevant for predicting part accuracy, because the measurement is made very nearly at the location of the tool tip with the machine moving at its cutting speed. The ball bar test measures the errors in table travel as it traverses a commanded circle.

The measuring instrument is a slender, extensible bar with a precision length sensor that measures the length of the rod. At each end of the rod is a precision steel sphere (the ball) that rides in a cup. One cup is fixed to the machine at the center of the circle, and the other cup is mounted on the moving head of the machine. See Figure 5.



The table is commanded to move in a circle with the nominal radius of the bar. Variations from nominal length are sensed by the length sensor and recorded on a PC attached to the bar. The angular position around the circle is determined by the time after start of motion so that a plot of length variation versus position around the circle can be determined. Such a plot is shown in Figure 6.



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DYNAMIC ISO 230-1
Circularity: 0.001876 in
Max: +0.000533 in, 170.2°
Min: -0.000543 in, 289.5°

BB624A01.RTB
By: BRETT BENSON
Machine: A511624
Date: 12:05 Jan 12 1999

Length:        5.905512 in
Radius:        5.905512 in
Best Radius:   5.905990 in
Centre Off X: +0.001014 in
Centre Off Y: -0.000300 in
Sample:    62.50 per sec
Feed:     161.9172 in/min

          Start  End
Machine 180.0° 180.0°
Data       0.0°   0.0°
2 runs, Bidirectional
```

Figure 6 Plot of ballbar measurement data

The errors from a true circle are plotted as a function of the angular position of the bar. In the plot in Figure 6, very small errors are due to the fact that the position is commanded in 0.0005-in. (0.013 mm) steps all around the circle. A slightly larger error is at the points where the axes reverse direction. Note that the scale of the plot is greatly magnified to 0.0005 in. per division.

Several sources for the errors may show up as bar length variation. The sources can be divided into low-speed, or static, errors and high-speed, or dynamic, errors. A test run at low speed will show only the static errors.

- Static errors may be caused by:
  - Ball screw pitch errors
  - Axis straightness and twist errors
  - Squareness errors between the two axes
  - Backlash in the mechanism
  - Loose belts
  - Flexibility in drive
- Dynamic errors may be caused by:
  - Axes vibration
  - Servo following error caused by loads from

    - Inertia
    - Friction
    - High-pressure plumbing loads
    - Direction reversal with a high integral gain
- Servo mismatch error

A single number representing the error found is the difference between the largest and smallest radius referred to as the circularity. The least part error one can expect from a table is the circularity. Other measures of accuracy may measure only static positioning accuracy or, at worst, only the lead error in the ball screws. In some cases machine accuracy can be improved with error-mapping.

Small tables may not require a foundation for accuracy, because it is possible to build a structure that is stiff over the length of the machine. Large tables are somewhat flexible, and the floor is an important element of the structure. Large tables (4 ft. by 8 ft. or 1.2 by 2.4 m, and larger) often are grouted or shimmed to the floor. For maximum precision, a thick, stiff foundation should be poured.

4.3 Sealing and Protection

The abrasive jet process, which includes large quantities of water and abrasive, is not friendly toward machinery. These elements can damage the abrasive jet machine and other nearby machinery. The best protection for the table axes are bellows that completely surround the linear bearings and ball screws and are sealed at the ends. But these bellows are impractical for very long axes, especially when the axes must be supported at one or more midpoints. In this case, a rigid enclosure with a downward-facing lip seal, that is opened by passage of the carriage, may be the best solution.

A worse configuration is U-shaped bellows sealed by their weight on a surface. Such bellows always have garnet under them, which is often blown under by a conscientious operator cleaning his machine with a blowgun.

Underwater cutting is a simple strategy for protecting the other machinery in your shop. With underwater cutting, the contamination is similar to that caused by grinding machinery. If cutting underwater is not possible, consider putting all of your abrasive jet machines in a common room isolated from the rest of the shop.

4.4 Machine Layout

A machine can be designed in multiple ways to move a nozzle around a workpiece. Some of these are shown in Figure 7.

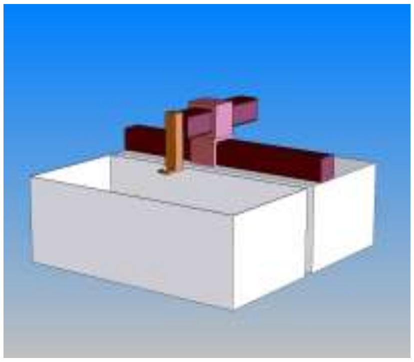
Figure 7a

Figure 7a shows a moving beam table in which the nozzle is affixed to the front of a beam that moves in and out across the tank. This design provides excellent access to the tank for material loading, but an area equal to the tank size is required behind the table to clear the back of the beam. The required floor size is double that of the machine design shown in Figure 7b, and for that reason, it is used for small machines only.

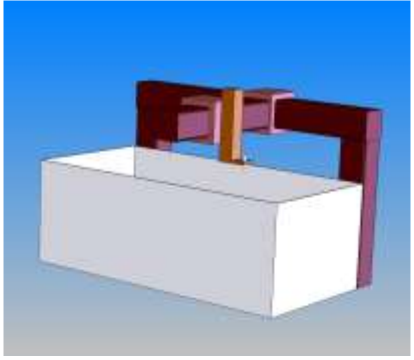
Figure 7b

Figure 7b's cantilever design provides almost the same access to the tank as the moving beam design with half the footprint, and it is suitable for even very large machines. The cantilever design provides access for working on plates larger than the table, and when the back beam is supported only at the two ends as shown, a long-plate workpiece can be fed under the beam.

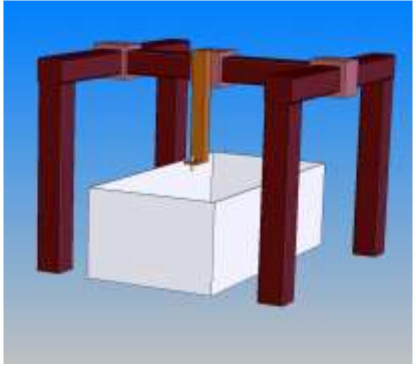
Figure 7c

Figure 7c shows a structure in which all of the mechanism is above the operator's head. It provides excellent operator access to the tank for removing cut parts by hand. Material can be loaded from the front with either a fork truck or overhead crane. This design also provides plenty of space for additional tilt axes and often is used for building full five-axis tables. The major disadvantage of this design is that the long Z axis makes the nozzle position sensitive to twist and bending errors in the overhead beams. Also, the long structural path between the table bearings and workpiece provides opportunity for errors caused by machine deflection.

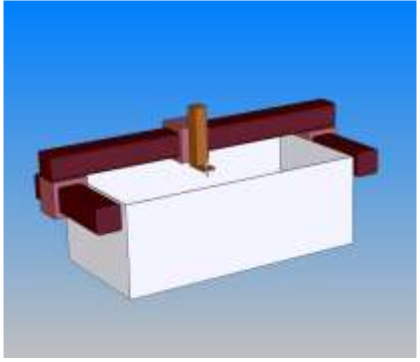
Figure 7d

Figure 7d shows what is perhaps the most inherently accurate construction. The bearings are very close to the plane of the work piece minimizing the errors discussed previously. Access to the tank is equal for material loading, but not quite as good for manual unloading.

4.5 Table Accessories

Many accessories are available for abrasive jet machines. Some tables are designed to accept a range of accessories; others are not. Some available accessories include:

- Programmable Z axis for following materials that are not flat.
- Automatic drill heads for piercing materials that would otherwise delaminate.
- Edge- and hole-finding devices for accurately referencing existing parts to the machine.
- Tilting head for controlling taper in the edge of the part.
- Joystick or pendant for moving the machine from a distance from the control.
- Automatic garnet removal system for keeping the tank clean.
- Garnet recycle system for reclaiming a fraction of the spent garnet.
- Water recycle system for cases in which draining to municipal systems is prohibited.
- Various fixturing and clamping devices.
- Rotary axes for tube cutting and production of small, 3-D parts.
- Terrain followers that hold the nozzle height constant on a warped plate.

5. SOFTWARE

Software plays a key role in abrasive jet machining. In fact, it is only through software that precision abrasive jet machining truly is possible. Some of the most significant advancements in the industry have been in software. This is great news, because it is far less expensive to upgrade software than it is to upgrade hardware!

5.1 The Cutting Model

Those new to abrasive jet cutting often wonder why software is so important to this technology in comparison to other cutting machines. The answer is that the abrasive jet is not a rigid tool that simply must be guided along a particular path to make a part. The jet bends and wobbles from side to side, and its shape is highly dependent upon the speed at which it is moved along the path.

Moving too slowly, the jet cuts a wider kerf at the bottom of the part than the top and also wastes precious machine time (see Figure 8a**).** Moving too quickly results in a wider kerf at the top of the part than the bottom, a poor surface finish, and the possibility that the jet may not cut through the material (see Figure 8b). Accelerating too hard at a corner causes the jet to kick back and damage the part.

5.2 Programming and CAD-CAM

The abrasive jet user is faced with the task of converting customer-supplied data in the form of either paper drawings or CAD files into instructions that run the machine. Software supplied by machine vendors for programming the machine can range from none to extensive, full-featured software, including CAD, cutting models, and even part nesting.

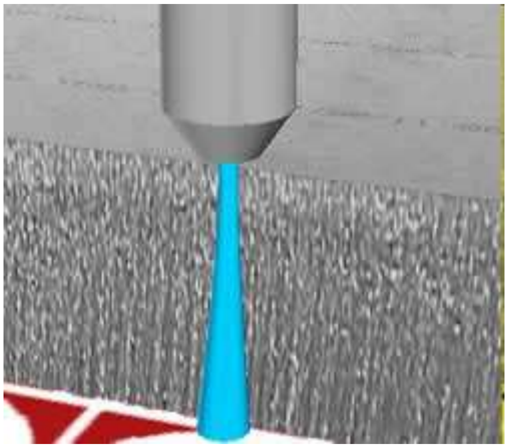

Figure 8 a) A jet moving at low speed is almost vertical and leaves a fine finish. But, cutting productivity is low.

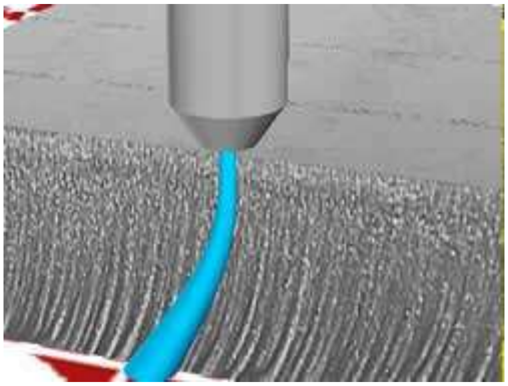

Figure 8 b) At high speed the jet bends. Ok on straight lines, but corners are damaged.

Early abrasive jet machinery was controlled with G-code controllers much like any other numerically controlled machinery. The user had to choose the feed rate at each point along the path, taking into account the material type and thickness and the cutting power of the particular jet. The motion commands, other than for speed, could be generated either automatically by a CAD-CAM program or by hand.

This type of programming is used primarily for five-axis work and is suitable for large production runs for which the cost of programming and tweaking the program can be written off over a large number of parts. It is also suitable for very rough work in which precision and surface quality are unimportant. Finally, it is sometimes used for one-of-a-kind work in conjunction with an experienced operator who continually adjusts the feed rate by hand, according to actual cutting conditions.

Alternatively, G-code programs may be written with a PC-based CAD-CAM system containing a cutting model which sets the speeds. This is a much faster programming method and can give better results than hand programming, but it is not ideal because G-codes do not generally contain commands for managing tool acceleration. Acceleration at corners is approximated by dividing the path and setting a different speed for each segment.

Finally, in some cases, the cutting model resides within the controller rather than the CAD-CAM system. These controllers can accept geometry from a variety of CAD-CAM systems in addition to the one provided with the machine. Thus, the user can choose to use the same system throughout the shop for running water jets, lasers and other machines.

These controllers automatically set the speeds based on the material type and thickness and on the part geometry (see Figures 9 & 10). They handle acceleration at corners to help avoid part damage due to jet kick back and tilt the head as a function of speed to eliminate slight taper caused by the jet.

Figure 9 a) Part made in Titanium

Figure 9 b**)** Complex velocity profile generated by a cutting model. Speeds are indicated by color ranging from blue (slow) to white (fast).

5.3 Controller and Operating Software

Once the part program file is prepared, it is taken to the machine and loaded into the machine controller. The machine controller is responsible for moving the cutting nozzle properly both in space and in time to produce the desired part. The machine controller also is the interface between the machine and the operator.

Figure 10 A good cutting model is especially important for making thick parts accurately.

Three categories of controls for abrasive jet cutting are available:

1. General-purpose G-code controllers.
2. PC-based controllers with plug in control cards containing the functionality of the G-Code controller.
3. PC controls with all software written by the machine builder.

The general-purpose G-code controllers are special-purpose computers built in low volume and using an operating system for which there is little or no second-party software. Graphics for help screens, teaching video, and network and Internet connections are possible but generally unavailable. Machine builders cannot modify the software to include such things as detailed velocity and acceleration control in the cutting model.

PC-based controllers with plug-in control cards can include help screens and video tutorials. Operation can follow standard PC conventions, and features such as networking or Web cameras for remote monitoring can be added at a minimal cost. Other features can include nesting, remnant management, history recording and reports, time and cost estimates, multiple home positions, and automatic zeroing.

Depending on the software, some of these controls can accept program files from a variety of CAD-CAM systems. In general, vendors of the control cards give the machine builders more control of the machine then control vendors do.

When the PC control software is written by the machine vendor, all features are the same as the controllers with plug-in control cards, except that the builder can implement the cutting model without compromise. Software is a major component of any abrasive jet cutting system. It affects the productivity and usefulness of the system in all but systems dedicated to long runs of the same part. A good cutting model can reduce the time to make a part by as much as a factor of 2 compared to programming feed rates by hand. The cutting model may reside either within the programmer's head, the CAD-CAM system or within the machine controller.

6. TAPER ELIMINATION

The balance between waterjet cutting production rate and part precision always has been difficult to achieve because of the jet’s complex behavior. Because its shape at any point along the tool path is a result of multiple independent variables — including the speed and acceleration with which it is moving — the jet is particularly difficult to manage. The cutting jet bends back along the path, flops from side to side, produces a speed-dependent tapered kerf, and produces a wider kerf when moving slowly. Precise parts can be made in spite of all these factors, but at the expense of the production rate, by moving slowly along the entire path.

One of the software’s roles is to manage the speed along the tool path as a function of the path shape, so that parts can be made more quickly while achieving the surface finish specifications. This section discusses software that automatically tilts the cutting head to make a square edge on the part while moving at higher speeds that normally result in a tapered kerf. Let’s begin by discussing some of the facts about taper.

6.1 Factors Affecting Taper

All of the independent jet cutting variables affect taper. Most of these factors are determined during cutting-rate setup. The only remaining factor of interest is the speed at which the jet is moved along the path. As the jet slows, the kerf moves from a taper widest at the top at high speed to a kerf widest at the bottom at extremely low speeds. Figure 11 shows taper over a portion of the speed range.

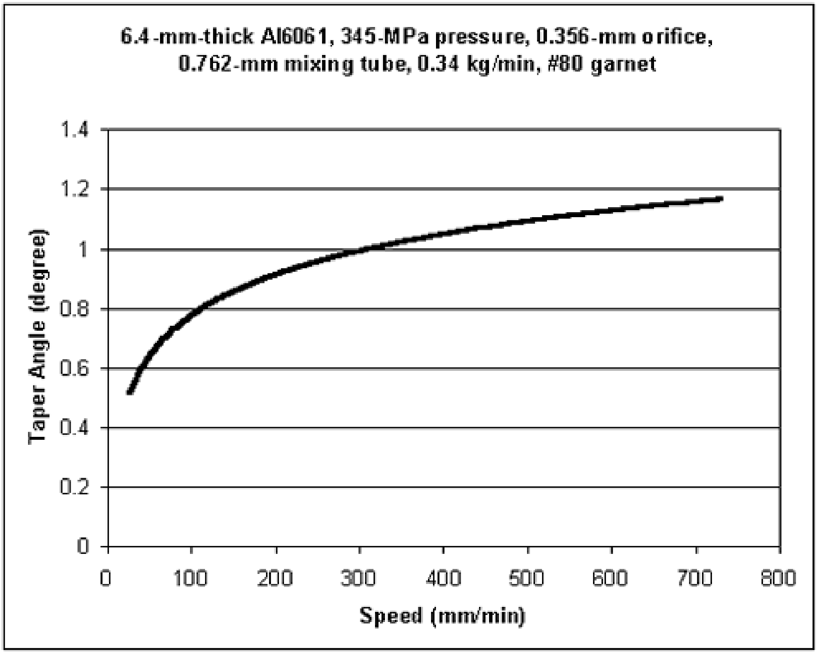

Figure 11 Taper Angle as a Function of Speed

Thin materials usually are cut at high speeds and thick materials are cut at low speeds. Thin materials may end up with more taper than thicker ones. Of course, if you cut 1/8-in. (3.2 mm) steel at the same speed as 2-in. (50 mm) steel, the taper could be nearly eliminated at a great sacrifice in productivity. Some software packages handle this variable by permitting you to assign a minimum taper quality to certain portions of the path. Doing so can eliminate the need to perform secondary operations to remove a taper and is justified in these cases.

6.2 Why Control Taper?

The primary reason for controlling taper is part accuracy and appearance. If your customer thinks the part looks bad because of the tapered edge, you can't sell it, and that is the end of the story. Taper often causes clamping problems during secondary machining operations.

Tapered parts are difficult to hold firmly in a chuck or vise. Often the first step of machining a jet-cut part is to make a skin cut to remove taper and allow solid clamping.

For some parts the cut surface must butt squarely against an adjacent part. A bolted joint is one example.

Sometimes the cut edge must run against another surface while carrying load evenly across the edge. Jet-cut gears, sprockets, and cams are examples of this part type.

Finally, a small amount of taper is desireable in some parts. Stamping dies and cutting tools require a small relief angle that can be formed with a tilting jet.

In all of these cases, taper control during the jet cutting process lowers cost by delivering a useful part without secondary processing.

6.3 Taper Control by Tilting

Two ingredients are necessary for removing taper by tilting the cutting jet—a mechanism for tilting the jet and software that correctly anticipates the taper and drives the tilting head accordingly. The tilting mechanism is attached to the XY table normally used without tilt. It is important that the center of rotation for the tilt be close to the point where the jet enters the top of the workpiece. Otherwise, keeping the jet entry point on the path would require large motions of the XY axes when tilt occurs.

Figure 12 shows a 2-D linkage that tilts on one axis and illustrates the principle involved. Note that the tool point moves only slightly as the tool is tilted. A similar mechanism with three linkage arms permits tilting in two directions, while keeping the tool point almost fixed. Note that the largest motion of the tip is in the vertical direction.

Figure 13 shows an actual head used for taper control. In this mechanism, one of the three linkage arms is driven in two directions by servomotors enclosed in the rounded housings. The remaining two linkage arms are enclosed in the small bellows.

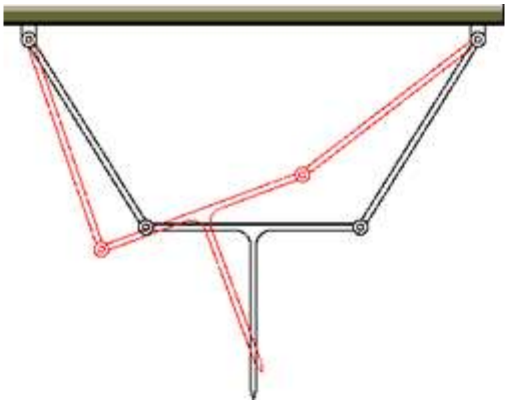

Figure 12 Simplified 2-D Version of Nozzle Tip Pivot Showing Two Positions

Because of the slight vertical motion of the tip as the head tilts, a compensating motion must be made in the Z direction. The cutting table then becomes a full five-axis machine with X, Y, Z and two angular axes.

No extra effort on the part of the operator is required to use a tilting head. However, the software has a very important job to do. In fact, the whole idea of tilting to remove taper was impractical with the computers available only 10 years ago. Everything needed for the tilting is done by the software in the following sequence:

1. The software uses a built-in cutting model to calculate the speed at every point along the tool path that is required to produce the desired part edge surface finish for the part material and thickness. This is the normal calculation for pure XY cutting that is done by the advanced controllers.

2. An extension of the cutting model that predicts taper is used to calculate the amount of tilt required to make a square edge or an edge with the desired taper.

3. The actuator commands are calculated from the desired tilt angles. In this step, slight adjustments to the X,Y, and Z actuator commands are made to compensate for the fact that the pivot point for the tilt is not exactly at the point at which the jet enters the material.

The computing time to accomplish steps 2 and 3 is about 20 times the time to complete step 1. At this point, the motion plan for the entire path is stored in the control memory and can be run multiple times to make multiple parts.

Figure 13 Tilting Head Attached to XY Table

Combining a jet tilting mechanism with taper-compensating software produces taper-free parts in fractions of the time it takes to make them simply by slowing down the process. Figure 14 shows two spur gears, standing side by side, made with the tilting head shown in Figure 13. The gears are resting on a surface plate next to an angle plate to show the squareness. These two taper-free gears line up so well that they appear to be only one gear. It took 2.2 minutes to make each gear from 1/4-in. aluminum using tilt and 31.7 minutes at the minimum taper speed without tilt.

Finer abrasives produce a finer surface finish on the cut edge, while cutting at the same rates as coarse abrasives. However, finer abrasives also produce a kerf with more taper than coarse abrasives. A tilting head removes this extra taper and, in fact, all taper so that there is no longer a taper penalty to achieving better edge finish.

7. SUMMARY

Figure 14 Gear Cut With Tilting Mechanism

Today abrasive waterjet cutting is a mainstream technology in modern machine shops. It can cut more and thicker materials than laser and does not produce a heat-affected zone. It cuts much faster than wire EDM. Modern abrasive waterjet machines can hold tolerances of ±0.005 inch (0.13 mm) or better. Some of them can produce taper-free parts with the latest tilting head technology. Two types of high pressure pumps, intensifier and crank-drive, are available to reliably produce 55,000 psi (380 MPa) working pressure. Crank-drive pumps cost less and are much more efficient while intensifier pumps have longer service intervals. XY tables for abrasive waterjet cutting are specially designed with proper size, precision requirements, as well as considerations on sealing and protections. Software plays a key role in abrasive waterjet machining. Besides the traditional role of CAD/CAM for a CNC machine, software for abrasive waterjet machines also determines cutting speeds and makes appropriate adjustments for minimizing the geometry errors and surface roughness caused by the deflections of the jet.

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