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ADVANCED ERROR CORRECTION METHODOLOGY APPLIED TO ABRASIVE WATERJET CUTTING

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Paper

ABSTRACT

First introduced in the last decade, the concept of “compute first, move later” for motion control optimized the abrasive waterjet cutting process. Using a cutting model that varied cutting speed around corners and along arcs provided a greater degree of accuracy. Recent innovations in corner-cutting strategy allow the cutting of external corners without sacrificing speed or surface quality. The latest development in machine-control hardware and software advances the error correction methodology in abrasivejet machining to the next generation. The nozzle automatically tilts along the cutting path, compensating for taper error as well as lag error at corners. A tool tip tilt mechanism lets the nozzle tilt quickly about the material entry point without large accelerations and vibrations. This paper provides insight into the development of these advanced error correction technologies as applied to abrasivejet cutting.

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1 INTRODUCTION

After two decades of development, abrasive waterjets have become a mainstream technology that works hand-in-hand with other machining technologies in modern machine shops. Abrasivejets cut five to ten times faster than EDM. While lasers are limited to non-reflective materials, abrasivejets are not. Abrasivejets can cut thicker materials than lasers, and the production cost is two-thirds less. Fixturing is less complicated on an abrasivejet than on a traditional machining center, and setup time is reduced. As the abrasivejet becomes accepted in more and varied applications, however, the challenges increase. Greater productivity (faster machining times) and higher accuracy are two constant and often contradictory challenges.

Consider the challenge of higher accuracy. These errors and defects can be found on parts machined by abrasivejets:

- Striation marks along the bottom half of the cut surface
- Jet lag errors at corners of the path and on small arcs
- Taper and barrel errors
- Geometrical error from kerf width change
- Lead-in and lead-out defects
- Frosting and rounding on top of the kerf
- Burrs at the bottom of the kerf

Previous work by Zeng et al. (1999) addressed striation marks and jet lag errors at corners of path and on small arcs. A jet shape modeling concept has been described by Henning and Anders, which shed light on real-time taper error compensation. The feasibility of such compensation was also proven later by Knaupp et al. A work by Groppetti et al. investigated edge rounding on top and burrs at bottom of the kerf. A study by Anderson and Johansson was devoted to lead-in and lead-out defects.

This paper presents a systematic approach for error correction starting from a new concept of motion control.

2 THE CONCEPT OF "COMPUTE FIRST, MOVE LATER"

A machine tool controller essentially does three things: it accepts a tool path as input, which is defined by a relatively small number of parameters; it provides a user interface; and it generates the physical position of a tool along multiple axes as a function of time.

Most machine tool controllers accept their input in the form of "G Code," consisting of sequential movement commands interlaced with On/Off commands for various machine functions. A three line sample of G Code is shown below:

```
000 G00 X1 Y2
010 M73
020 G01 X2 Y3 F120
```

In this example, the lines are sequentially numbered in steps of 10. The first line indicates that the nozzle should move to coordinates X1, Y2 at a preset rapid traverse speed. The next line turns on something, such as a cutting jet. The third line moves the nozzle to coordinates X2, Y3 at a speed of 120. The controller executes these commands one at a time, and performs any calculations necessary to coordinate the multiple axes as the motion proceeds. Some controllers process a few lines ahead, helping to manage accelerations at sharp turns of the path.

This code can be written by hand or generated automatically with a CAD/CAM program. Note that this type of controller requires the exact motion path and the desired speed of motion as input. The part shape and the tool path shape usually have a one-to-one relationship independent of the speed and accelerations along the path in machining applications. But this assumption is not true for abrasivejet cutting.

In 1996 a patent was issued on a different control mechanism called "compute first, move later." This control mechanism was developed specifically for abrasivejet cutting. The same functions are performed, but by using the large memory and computing power of modern personal computers, they may be performed in a different order. In this type of controller, the part shape is first described by a series of lines and arcs, much like the G Code representation, but without any data regarding speeds of motion. The entire tool path is then interpolated with speeds set according to a model of the abrasivejet cutting process. At this point, the path is stored digitally in a large data array with about five kilobytes per centimeter of the tool path. Here it can be iteratively manipulated to correct for various abrasivejet behaviors, producing a part of the desired shape and tolerance.

The ability to process the entire path iteratively is a major advantage in abrasivejet machining. First, there is the ability to look ahead for the entire length of the path. In a thick material, a sharp corner near the end of the path may require the abrasivejet to slow at the start of the path. In a thin material, high speed on a straight portion of a path may require tilting of the nozzle to avoid taper on the edge of the part.

The error correction phases described below manipulate the large data array that represents the path by changing the speeds as a function of path geometry, and by inserting tilting motions to compensate for the natural taper produced by the abrasivejet. This results in more accurate parts.

3 ERROR CORRECTION PHASE 1: REDUCING GEOMETRICAL AND COSMETIC ERROR

On parts cut with an abrasivejet, the most profound errors are the striation marks and jet lag errors at corners and arcs. These errors often make the parts either cosmetically unacceptable or outside of tolerance requirements.

An abrasivejet cutting model was published by Zeng et al. in 1992. The model predicted the cutting speed for a given quality index, combined with other process parameters. By selecting a proper quality index in the range of one to five, the striation marks along the cut surface are partially or completely eliminated. Choosing a quality index of "one" creates a separation cut, a very rough cut without any concern for surface finish. Choosing a quality index of “five” creates a smooth and striation-free surface.

Employing a similar idea, the amount of permissible jet lag errors at corners and arcs is used to calculate an effective quality index. This effective quality index depends on the angle of corners, and the radius of arcs. The result of using the effective quality index at corners and arcs is a reduced cutting speed at these locations.

By using the “compute first, move later” concept and the PC-based software infrastructure built on this concept, the transition of cutting speed at corners and arcs can be conveniently handled at increments of one motor step. In practical terms, this means the cutting speed can be varied every 12 microns or so along the path. Varying the speed one motor step at a time is a vast improvement over the traditional CNC controller—it allows higher cut quality at corners.

4 ERROR CORRECTION PHASE 2: BALANCE OF SPEED AND QUALITY

These advances to abrasivejet machining technology have been available since 1993. Since then, the technology has been improved even further—the cutting process is faster, and cuts are more precise. Some of the more recent enhancements include:

- Automatic setting of lead-in length and speed based on a pierce model, providing the fastest possible dynamic piercing
- A new cornering strategy that treats every possible corner geometry uniquely
- Automatic addition of “corner passing” based on a cutting model built into the software, speeding up outside corners where there is room to do so

4.1 Stage 1: Piercing

There are many ways to pierce a material. A material can be pre-drilled mechanically, pierced by a stationary abrasivejet, pierced by moving the jet back and forth over a fixed distance (“wiggle” piercing), or dynamically pierced by turning on the abrasivejet and then slowly moving across the material. Each of these has its advantages, and each is appropriate for different situations. The two most popular methods are dynamic piercing and wiggle piercing, because they generally offer the fastest piercing with the most convenience for a wide variety of applications.

Wiggle piercing has been a good balance between fast piercing, short pierce distance, and ease of programming. It is generally faster than most implementations of dynamic piercing, and is especially good for piercing thick material in small spaces, such as piercing a 6 mm hole in 5 cm thick steel.

Dynamic piercing is limited by the difficulty in determining and setting the ideal lead-in length and speed for each pierce point in the path. This is solved with the use of a dynamic piercing model that looks at the machining conditions and automatically sets the pierce length and speed based on the geometry of the part and the pump and nozzle setup.

Using this model, it is possible to greatly speed up piercing performance without any user intervention or knowledge of the process. If a tiny hole is being pierced, then the lead-in will shrink, and the piercing speed will be reduced to make up for the loss of room. If the hole is larger, the pierce length will increase to the optimal length, and the speed will be increased appropriately. This makes dynamic piercing ideal for most applications, with the exception of small holes in thick materials, where wiggle piercing may still be the preferred choice.

4.2 Stage 2: Corner Corrections

The main drawback of earlier controller technologies was that the controller treated outside corners with the same cutting model parameters as inside corners. The controller slowed more than necessary for outside corners.

By applying separate cutting models to inside and outside corners, both speed and precision are improved. Outside corners can be machined much faster, and inside corners can be machined at precise speeds and accelerations that minimize blowout and kickback more than previously possible.

4.3 Stage 3: Corner Passing

Corner passing refers to the concept of overshooting a corner, reversing the abrasivejet, and then continuing along the tool path. The advantages of corner passing are that software can program the corner passes automatically and determine the best geometry to use, adding corner passes only when and where needed

To use corner passing, software first computes how much jet lag there will be at each outside corner by using the built-in cutting model. If there is room to do so, the software automatically adds a short element slightly longer than the length of one jet lag past the corner.

This allows the controller to move the abrasivejet at full speed past the corner. The controller then accelerates back to the corner, and continues cutting. All this motion occurs at virtually full cutting speed, allowing for dramatically faster machining of outside corners.

Figures 1 and 2 show the same tool path calculated for 2.5 cm thick mild steel. Lighter areas show fastest abrasivejet motion while darker areas are slower. In Figure 2, the lead-in length has been increased for dynamic piercing, outside corners are treated differently than inside corners, and corner passing allows for even faster jet motion.

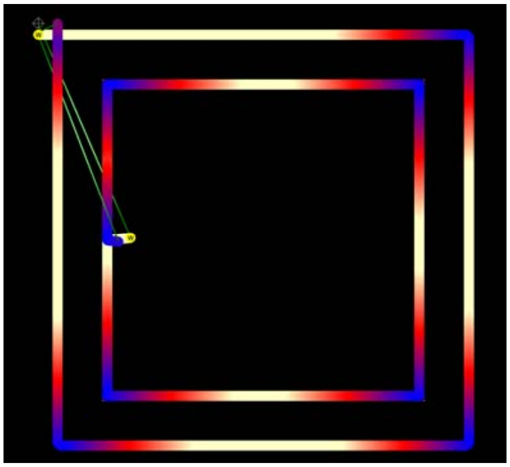

Figure 1. With no optimizations other than basic corner compensation, the part takes 17.1 minutes to machine.

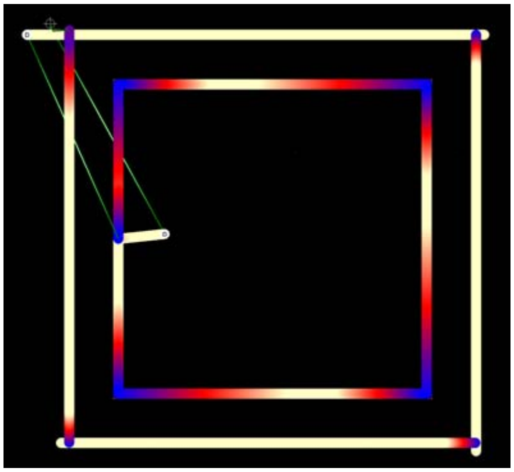

Figure 2. With the addition of optimized dynamic piercing, corner strategy, and corner passing, machining the part speeds up to 13.7 minutes.

Tests showed that for 150 different parts ranging from mechanically simple parts to complex artworks, an average speed increase of 128.4% was achieved. One part machined slightly slower (98% of previous speed), 14 parts machined in excess of 150% faster, and one part had a machining speed increase exceeding 200%. Tests were done with several material and thickness settings.

The parts also come out to slightly higher tolerance. By slowing down less on outside corners, there is less opportunity for the kerf width to grow. Figure 3 shows a 20 cm thick aluminum rectangle machined using corner passing.

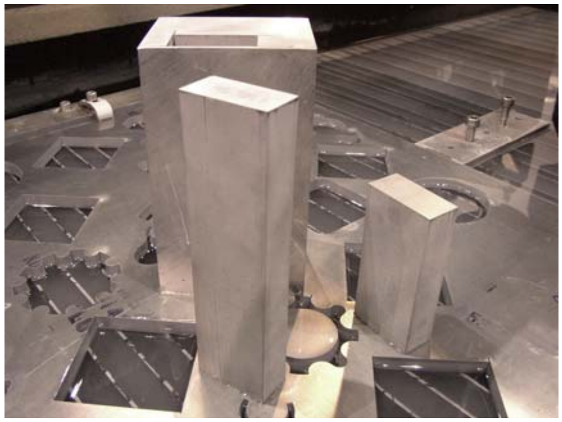

Figure 3. A 20 cm (eight inch) thick aluminum rectangle machined using corner passing to improve the quality of the outside corner, while simultaneously speeding up part cutting significantly

Figure 4. A high tolerance part machined from 1 cm (0.4") stainless steel.

In Figure 4, notice the high quality inside corners. While the corners are not perfect, the amount of washout has been reduced to almost nothing. The sharpness of the inside corner, therefore, becomes primarily a function of the nozzle diameter. Corner passing increases the tolerance of this part by preventing excess kerf width growth from slowing down around outside corners.

5 ERROR CORRECTION PHASE 3: ELIMINATING TAPER

5.1 Adaptive Cutting with a Tilting Nozzle

The third phase of error correction is the easiest to understand, but the most difficult to implement. The nozzle needs to be tilted by an amount sufficient to remove the natural taper of the jet stream. Implementation of this concept requires three things:

- Predicting the amount of taper caused by the jet stream
- A mechanism for mechanically tilting the jet
- A five-axis control system capable of producing the required coordinated motion

As discussed previously, the nozzle speed must be varied along the path to achieve sharp corners and precise radii. As shown in Figure 5, the shape of the taper produced by the jet is a function of speed. Thus, the nozzle must tilt to different angles along the path according to the speed of motion.

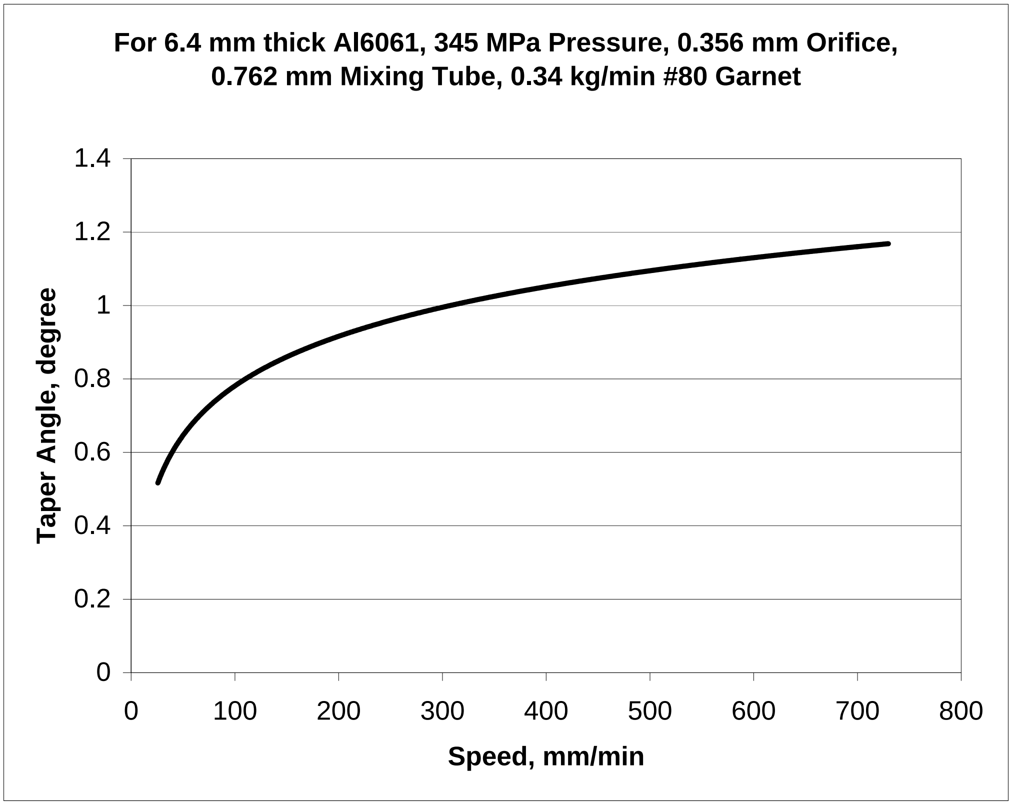

Figure 5. Taper angle as a function of speed

5.2 Tool Tip Tilting Mechanism

The mechanism for tilting the nozzle must provide quick response to follow the angle required by the X-Y path motion. Typically, the tilting mechanism will be carried on a large X-Y table used for cutting parts from plates of material. Quick motions of the tilt head imply high accelerations of the X-Y mechanism, unless the tilting mechanism pivots about the nozzle tip.

A patent application has been recently filed for a mechanism closely approximating a nozzle tip pivot and reducing the accelerations required by the X-Y mechanism. The mechanism is easiest to understand by first considering a two-dimensional simplified version (see Figure 6).

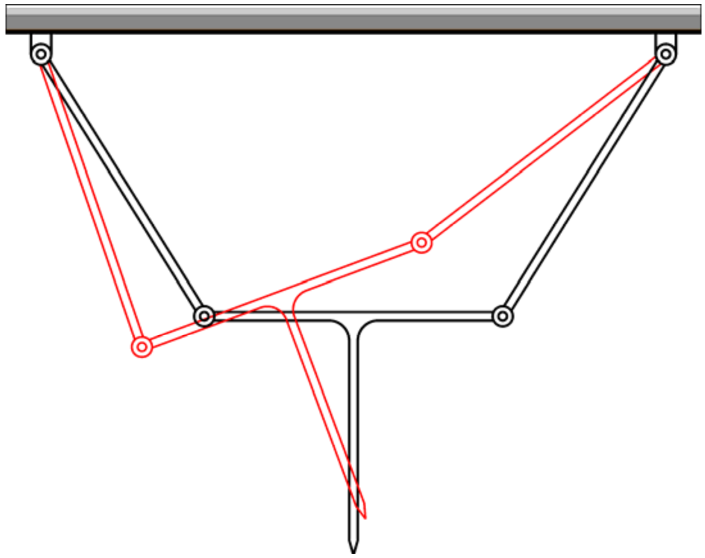

Figure 6. Two-dimensional simplified version of nozzle tip pivot, showing two positions

A nozzle is mounted on a plate, supported by two links connected to a stationary top plate. When the plate moves sideways, the nozzle tilts while the tip remains almost stationary. For the small angles needed to remove taper produced by the jet, the X-Y axes need to move only a few tens of microns to compensate for the tip motion.

This idea was then extended to a three-dimensional mechanism where a third link is added and the lines defined by the three-link spherical pivots join at the nozzle tip. The three-link mechanism has one more degree of freedom than the two-dimensional example in Figure 6. Adding this degree of freedom also means the movable plate can twist about a vertical axis. For the device to be useful, this motion must be controlled. The motion is restrained by replacing one of the links with a drive shaft that has a universal joint at each end. A photograph of a prototype of this mechanism is shown in Figure 7 where a ball has been placed at the tool tip location for testing.

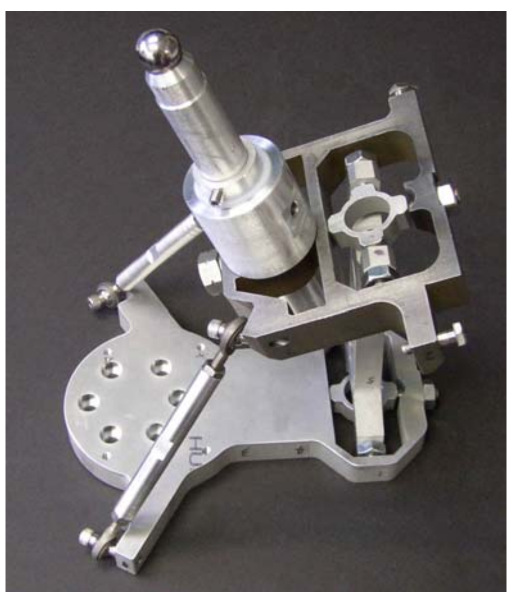

Figure 7. Early prototype of tool tip tilting mechanism

The prototype shown in Figure 7 was driven with two linear actuators that moved the tilting plate attached to the nozzle. After some experimentation with the model, it became obvious that a simpler and more compact mechanism could be built by actuating the yokes of the universal joints with rotary actuators. Figure 8 shows a solid model of the final design now in production.

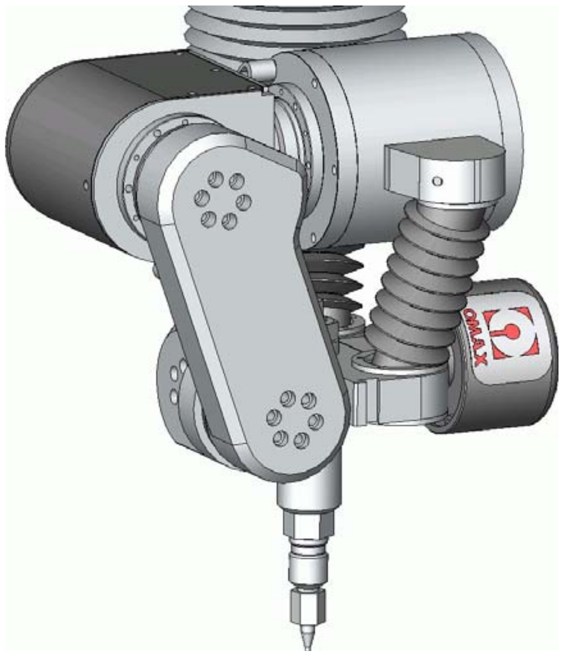

Figure 8. Solid model of final design for tool tip tilting mechanism

The software for implementing the tilt begins with the tool path corrected for the other jet errors. The speed at each point in the path is known, so the taper angle normal to the path motion can be calculated. A calculation is then performed to find the required positions for the two rotary actuators that drive the universal joint yokes. For all but the smallest angles, the tilt requires a slight correction to the positions of the X, Y, and Z actuators. This correction is added, and the software performs the same operations at the next point on the path. At present, this calculation is performed at 790 points per centimeter of the tool path.

5.3 Taper Modeling

Experience shows that taper is affected by process parameters such as material thickness, type of material, size of nozzle, and size of abrasive particles. An experimental pilot study on quantifying taper was done a few years ago. This screening experiment evaluated 11 variables: material machinability, thickness, water pressure, orifice diameter, mixing tube diameter, mixing tube wear condition, abrasive material, abrasive mesh size, abrasive flow rate, stand-off distance, and quality index.

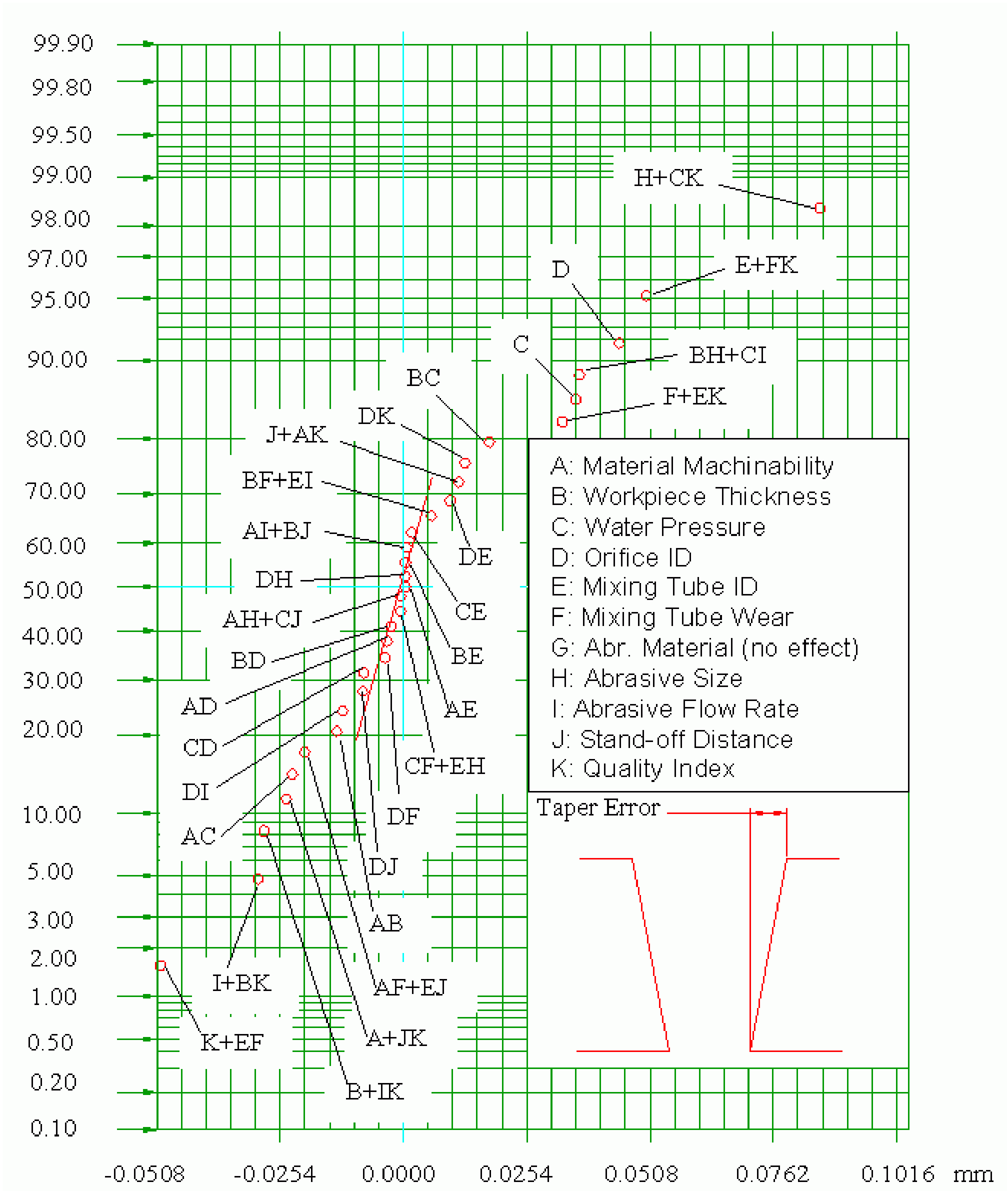

Figure 9. Effects of process parameters on taper error

The results are illustrated in Figure 9. The main effect of each variable is showed as a single letter, e.g., letter "D" stands for the main effect of the orifice inside diameter (ID). The interaction effect of two variables is showed as a two-letter word, e.g., "AB" stands for the interaction effect of machinability and thickness. In some cases, a main effect may be confounded with an interaction effect such as "H+CK." Since interaction effects are usually small compared to main effects, this graph is still useful as a tool to sort out the main effects. Those effects on or close to the straight line that passes through "0.0000, 50.00" are considered noises and are ignored. Those far away from the straight line are important effects.

The pilot study showed that seven of the variables were most important in determining taper and therefore, an experiment with seven variables could be implemented to develop the taper model. The seven variables were abrasive size, orifice inside diameter, water pressure, quality index, abrasive flow rate, workpiece thickness, and machinability. Even though the mixing tube inside diameter has a strong effect on taper, it was not considered as a variable in this experiment because of the fixed ratio between the inside diameter of the mixing tube and the orifice.

The resulting model is a quadratic function of main effects and interactions with a total of 28 terms. Figure 10 shows the correlation between the model and the observed taper errors, which shows the model predictions agree quite well with the observed values.

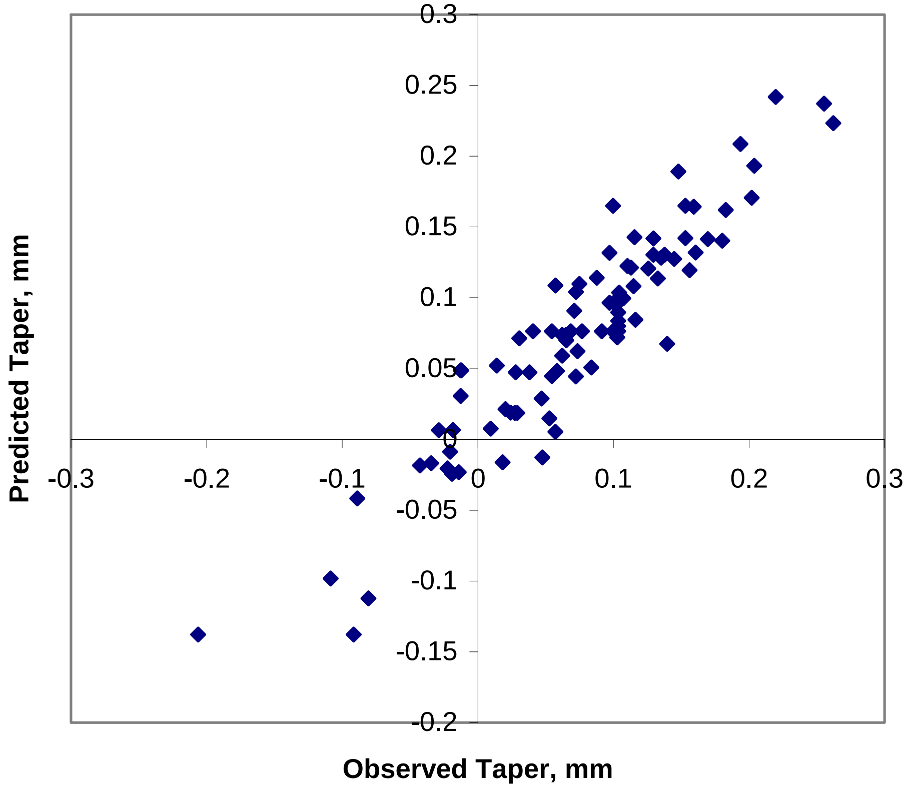

Figure 10. Predicted vs. observed taper error

5.4 Experimental Results

Figure 11 shows two 50 by 50 mm squares (6.4 mm thick aluminum) machined with and without the tool tip tilting mechanism. Taper measurements were done using a dial indicator accurate to 2.5 microns, on seven spots evenly spaced across the 50 mm length of two opposite sides. The results are shown in Table 1.

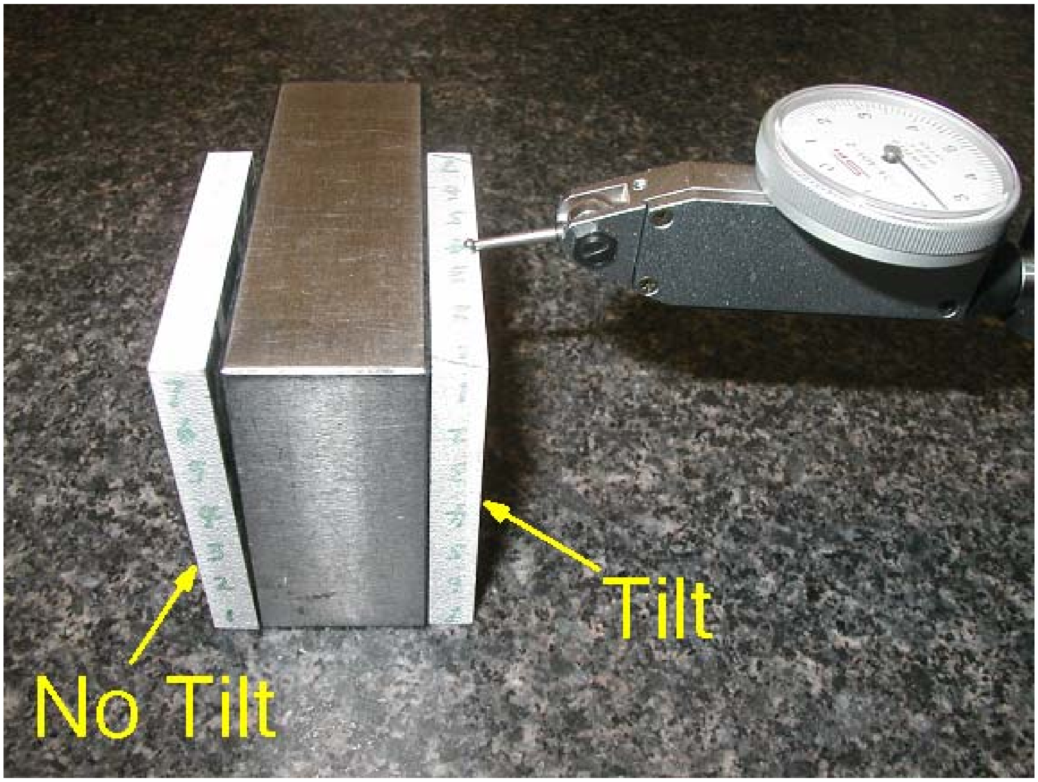

Figure 11. Samples cut with and without the tool tip tilting mechanism

Table 1. Taper Measurements (mm)

Spot No.			1	2	3	4	5	6	7	Average
No Tilt	Side A	Top	0.000	-0.013	-0.018	-0.010	-0.023	-0.013	-0.025	
		Bottom	0.183	0.183	0.183	0.183	0.183	0.180	0.183	
		Taper	**0.183**	**0.196**	**0.201**	**0.193**	**0.206**	**0.193**	**0.208**	**0.197**
	Side B	Top	0.000	-0.003	-0.010	-0.010	-0.013	-0.005	0.005	
		Bottom	-0.008	0.005	-0.015	-0.033	-0.020	-0.020	-0.025	
		Taper	**-0.008**	**0.008**	**-0.005**	**-0.023**	**-0.008**	**-0.015**	**-0.031**	**-0.012**
Tilt	Side A	Top	0.000	0.005	0.010	0.003	0.003	0.003	0.008	
		Bottom	-0.010	-0.013	0.028	0.025	0.010	0.023	0.013	
		Taper	**-0.010**	**-0.018**	**0.018**	**0.023**	**0.008**	**0.020**	**0.005**	**0.007**
	Side B	Top	0.000	-0.015	0.000	-0.018	-0.020	-0.008	-0.005	
		Bottom	-0.015	0.005	-0.008	0.008	-0.008	0.015	0.018	
		Taper	**-0.015**	**0.020**	**-0.008**	**0.025**	**0.013**	**0.023**	**0.023**	**0.012**

Without tilting, the sample shows a taper error of 0.197 mm on one side and –0.012 mm on the other. The difference in taper error on these two sides indicates a perpendicularity error between the nozzle and the sample surface. The average taper for both sides is 0.092 mm (0.0036 inch).

Using the tool tip tilting mechanism, the taper errors on the sample are 0.007 and 0.012 mm on the two opposite sides. The average is 0.009 mm (0.0004 inch) and the difference between the two sides is 0.005 mm (0.0002 inch). Both the taper error and the perpendicularity error were corrected.

To demonstrate that the tool tip tilting mechanism is able to handle more sophisticated patterns, two parts of a gear pattern were cut as shown in Figure 12.

Figure 12. Gears cut with tool tip tilting mechanism

6 CONCLUSIONS

The method of "compute first, move later" allows sophisticated calculations and adjustments for error correction at every motor step. The use of a cutting speed model combined with the ability to vary the tool path speed one step at a time provides a convenient way to minimize the striation marks and most jet lag errors at corners and arcs. Innovative techniques such as corner passing and multiple-acceleration schemes enhance productivity and quality at the same time. Finally, the development of a patent-pending tool tip tilt mechanism and a taper model improves the quality of abrasivejet machining by eliminating taper.

7 REFERENCES

Anderson, U. and Johansson, B., “Cutting Quality Improvement by Start and Stop Procedures for Closed-Contour Cutting,” *Proceedings of the 16th International Conference on Water Jetting*, October 16-18, 2002: Aix-en-Provence, France, pp 259-266.

Groppetti, R., Gutema, T., and Lucchio, A. D., “A Contribution to the Analysis of Some Kerf Quality Attributes for Precision Abrasive Waterjet Cutting,” *Proceedings of the 14th International Conference on Jetting Technology*, September 21-23, 1998: Brugge, Belgium, pp 253-269.

Henning, A. and Anders, S., “Cutting-Edge Quality Improvements through Geometrical Modeling,” *Proceedings of the 14th International Conference on Jetting Technology*, September 21-23, 1998: Brugge, Belgium, pp 321-328.

Knaupp, M., Meyer, A., Erichsen, G., Sahney, M., and Burnham, C., “Dynamic Compensation of Abrasive Water Jet Properties through 3-Dimensional Jet Control,” *Proceedings of the 16th International Conference on Water Jetting*, October 16-18, 2002: Aix-en-Provence, France, pp 75-90.

Olsen, J. “A Bend in the Stream,” *Cutting Tool Engineering*. Volume 48, Number 1, February 1996.

Zeng, J., Kim, T.J., and Wallace, R.J., “Quantitative Evaluation of Machinability in Abrasive Waterjet Machining,” *Proceedings of the 1992 Winter Annual Meeting of ASME*, “Precision Machining: Technology and Machine Development and Improvement,” PED-Vol.58, Anaheim, 1992, pp 169-179.

Zeng, J., Olsen, J., and Olsen, C., “The Abrasive Waterjet as a Precision Metal Cutting Tool,” *Proceedings of the 10th American Waterjet Conference*, August 14-17, 1999: Houston, Texas, pp 829 – 843.