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CUTTING AND SHAPING OF THICK MATERIALS WITH AWJ

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ABSTRACT

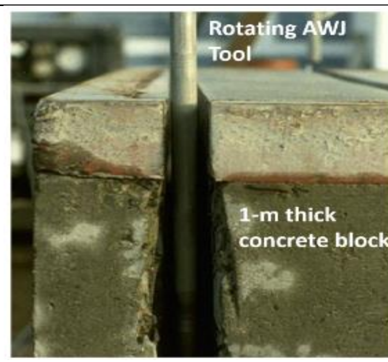
AWJs have been used of cut relatively thick materials such as concrete, titanium, steel, and glass. In order to improve the accuracy of the cuts, some techniques have been developed such as jet angulation, increasing the power and power density of the jet. The measurement of two dimensional edge cuts was used to determine lead and taper angles for improved geometrical results using models. It was found that relatively large power jets are needed to insure cutting faster and with minimal wall waviness. For example, 200 kW jets were used to cut glass honeycomb shapes up to 600-mm thick with thin (~ 1-2 mm thick struts) out of a solid block. Titanium and steel up to 300-mm thick were precisely cut for jet engine applications. Both taper and undercutting around corners were either minimized or eliminated using jet lead and taper angle control. Shaping with AWJ is emerging in some applications to save material and reduce overall production time.

1 INTRODUCTION

One of the important advantages of abrasive-waterjets (AWJ) over other beam-like cutting tools such as laser is their ability to cut relatively thick materials whether hard as steel, glass, and stone or soft as foam and plastics. There are a few methods by which an AWJ can cut relatively thick (~> 50mm – 600 mm) materials. These are:

- Single pass cutting: In this case, a jet is used to cut through the material in one pass. Typically, the thicker the material, the higher the power of the jet that will be needed to achieve the machining results. This paper is focused on this approach.
- Multiple pass cutting: In this technique, several passes are used to groove deeper into the material. The standoff distance increases with every successive pass and accordingly the cutting capability will be reduced. It was observed (3, 4) that there is an optimal combination of traverse rate and number of passes to achieve maximum cutting depth or highest productivity. This topic will not be covered in this paper.
- A penetrating tool may be needed to make deep cuts. However, the kerf must be widened in order to allow the jet nozzle to enter the kerf. Widening the kerf may be accomplished by rotating or oscillating a slightly angled jet while traversing. With this method, over 1-meter deep cuts were made in nuclear-grade reinforced concrete using 100 kW AWJ producing 0.5-1.0 m^2/hr cut area rate. This was used as a tool for decommissioning the west valley nuclear services facility in NY. This method will not be covered in this paper, but the reader may refer to (5).

Figure 1 shows examples of AWJ cuts made in thick materials using the above methods. In this paper, we will start first by discussing the general features of AWJ cuts as pertains more to cutting thick material. This will be followed by discussing some theoretical aspects of deep cutting. Some cutting observations will then be presented for glass, steel, and titanium. Conclusions are then presented at the end.



Cuts in 150-mm thick Titanium	Penetrating AWJ Tool in 1-m thick concrete

Figure 1: Examples of AWJ Cuts made with Different Techniques

2. AWJ KERF GEOMETRY

As the abrasive waterjet (AWJ) cuts through and separates the material, three phenomena are observed (6-9). The first is that the jet is deflected opposite to the direction of the motion. This means that the exit of the jet from the material lags behind the point at the top of the material where the jet enters. The distance by which the exit lags the entrance is typically called the trail-back, lag, or drag as shown in Figure 2. Observe that the jet-material interface is a curved surface.

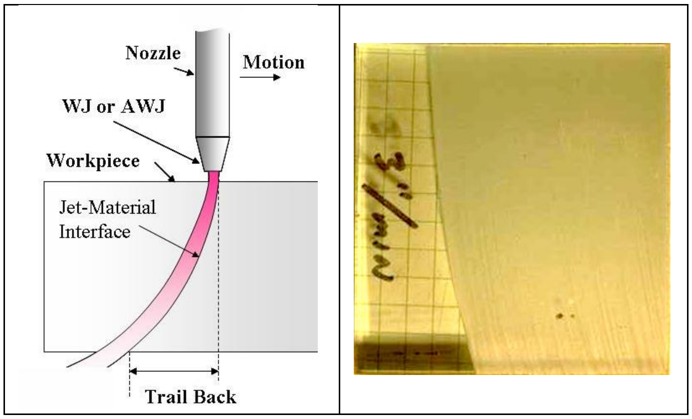


Figure 2: Trail Back

The second phenomenon is that the width of the cut varies along the cut from top to bottom. This difference in width is typically called the *taper* of the cut. A *taper* can be either positive or negative, that is, the width at the exit of the cut may either be smaller or larger than the width at the top. Typically, the kerf width at the exit side is smaller than that at the entry at practical cutting speeds. Figure 3 shows cuts with different taper.

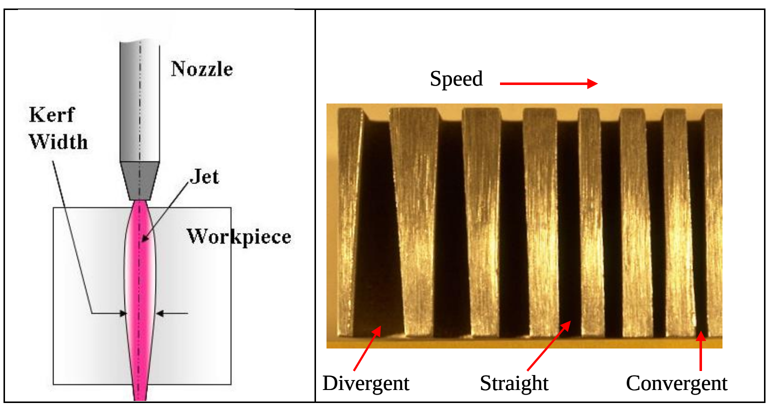


Figure 3: Taper Examples in Steel

For shape cutting, the trail back and taper phenomena manifest themselves in distortions to the geometry of the cut at the exit side. The sketch in Figure 4 shows an undercut due to the trail-back phenomena. The picture in the same figure shows distorted square-shaped cuts at the bottom surface of the material due to trail-back and taper.

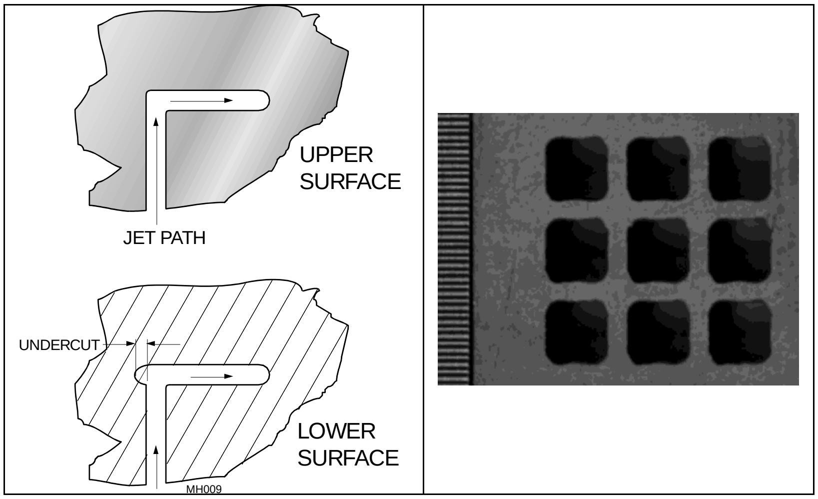


Figure 4: Undercutting at the Bottom of Cuts

The third phenomenon is related to the surface finish of the cut. Due to the transient nature of the jet penetration process and jet instability, striations will form along a cut surface, especially near the exit. Figure 5 shows typical striated (wavy) surface produced by AWJ.

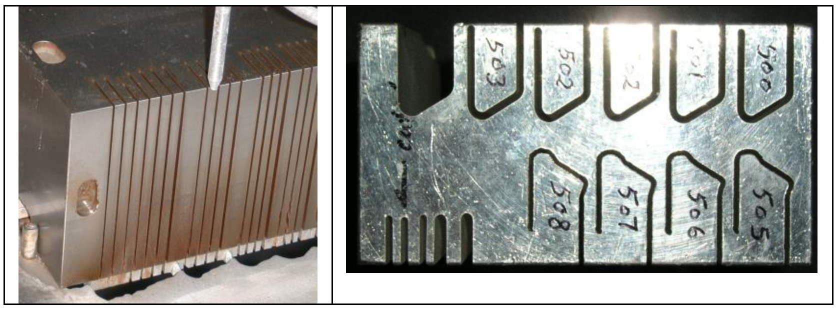
Figure 5: Surface Topography

3. BASIC STRATEGY

The basic strategy for relatively accurate cutting of thick materials is related to both process and kinematic issues:

- Process Issues: The AWJ process parameters should be selected to cut the required depth at the required speed and surface quality. For a given jet power, the speed of cut can be determined based on the required surface quality as typically used in current practice. Typically, deeper cuts require larger jets and thus higher levels of hydraulic power and abrasive flow rates. A special AWJ nozzle design (10) may be needed to maximize the use of the available power. For example, a mixing tube length of 600-mm was used to precisely cut 300-mm thick glass using 200 kW jet. Other process issues are related to the steadiness of the parameters such as pressure and abrasive flow rate.

- Kinematic Issues: Deep cutting, especially when geometric precision and low surface waviness are required, is more sensitive to the quality of the motion system meeting accurate traverse rates with minimal deviations. Also, if jet tilting (11) is needed as may be required for three dimensional cutting or for kerf shape compensation, then the accuracy and strategy of jet tilting must be considered. Jet angulation parameters can be determined experimentally by measuring the no-tilt two dimensional trail-back and width of cut profiles and then mathematically determining the lead and taper angles to minimize deviations. Figure 6 shows short straight nibble cuts used for this test. Also, short shape nibble cuts are used to determine the undercut parameters.



Straight Nibble Cuts in 100-mm Thick Steel	Shape Nibble Cuts in 100-mm Thick Glass

Figure 6: Straight and Corner Nibble Cuts to Characterize Kerf Geometry

4. OBSERVATIONS AND THEORETICAL TREATMENT

In this section, we present experimental observations and some simplified models.

4.1 Leading Kerf Shape

As mentioned above, the trail-back phenomenon becomes more significant as depth of cut increases. Figure 7 shows trail-back data for cutting 300-mm thick titanium 6AL-4V at different conditions.

Observe that the trail-back curve is generally circular in nature and that the radius of curvature is dependent on the AWJ process parameters. A simple model for the shape of the trail back is a parabola in the form $t_b = k\, x^2$, where k is a constant for every curve and x is the depth. Changes from one curve to another (k value) depend on the process parameters such as traverse rate, abrasive flow rate, and jet structure. Studies (12-14) have also addressed modeling studies of this kerf shape. Figure 8 shows that all the trailback curves can be normalized using a model.

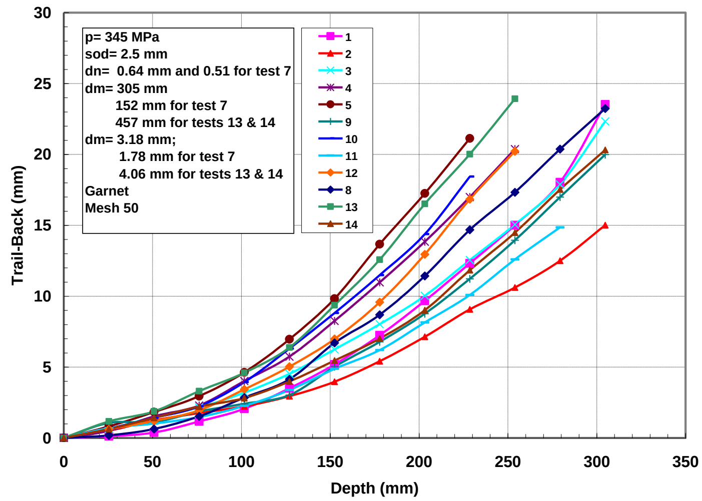


Figure 7. Trail-back Geometry for Several Cuts in Titanium

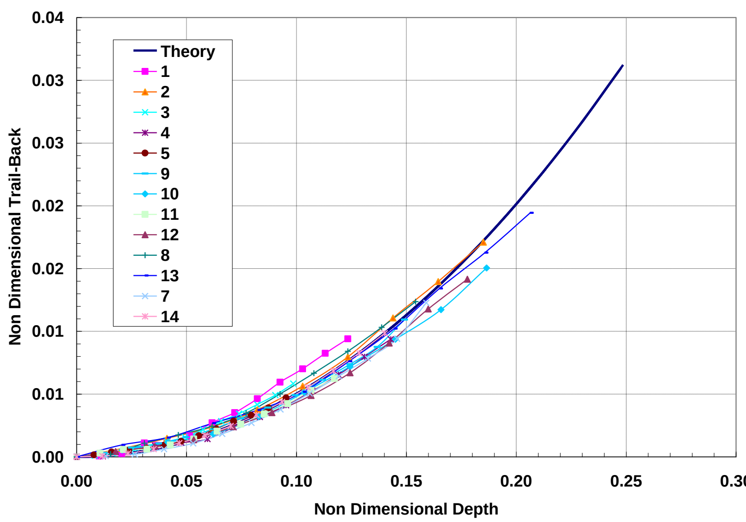


Figure 8: Normalized Kerf Shape Data and Comparison to Universal Kerf Shape

In order to minimize the effect of trail back on the cut geometry, jet angling with a lead angle will be needed. Figure 9 shows data for 300-mm thick titanium cutting at normal impact angle and at different lead angles. Observe that at a lead angle of approximately 3.39 degrees, the maximum trail back occurs near the middle of the part thickness. The amount of this trail-back is about 4-mm at this angle versus 17-mm when no lead angle is used. This dramatic reduction in trail-back is of course due to the shape of the jet-material interface curve. For shallow cuts, where this shape is close to a straight line, the trail-back can be reduced to nearly zero when the appropriate lead angle is used. This is of critical importance when machining precise parts.

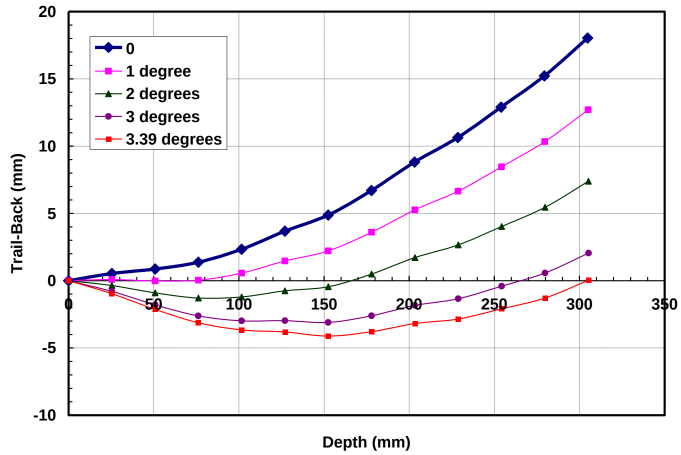


Figure 9: Effect of Lead Angle on Kerf Shape and Trail-Back

4.2 Kerf Width

It has been observed that the AWJ-produced kerf profiles are similar to those shown in Figure 10. For example, Figure 11 shows kerf width data for 300-mm thick titanium at the same conditions shown in Figure 7 above. Observe that most of the kerf profiles are converging as the traverse rate was relatively high to produce a divergent shape profile.

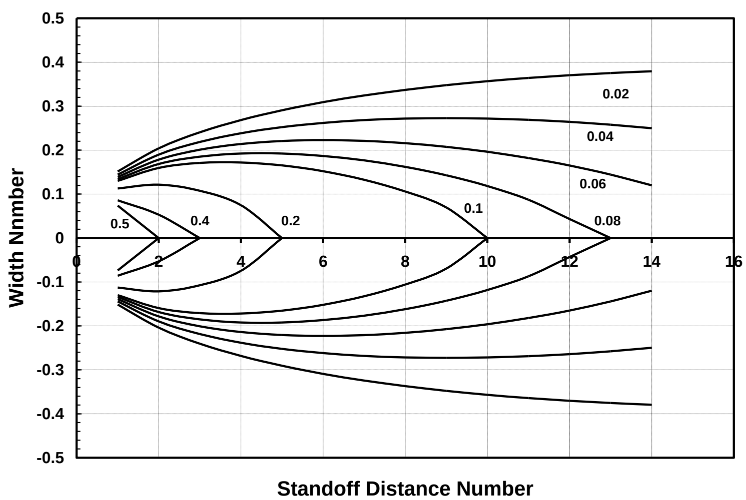


Figure 10: Theoretical Waterjet Kerf Profiles (15)

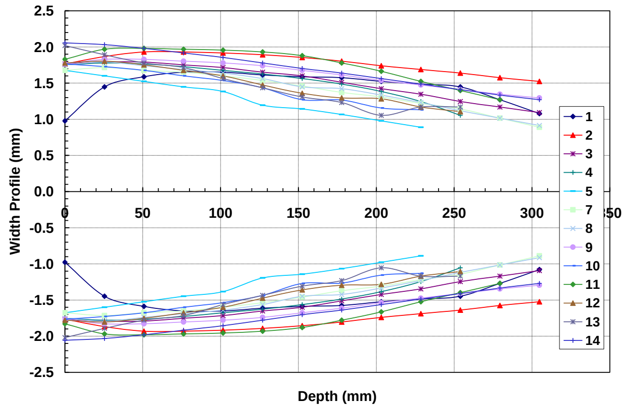


Figure 11: Kerf Width Profile in 300-mm Thick Titanium

Similar to rotating the kerf shape using a lead angle, the kerf width profile can be rotated to minimize taper on one side of the cut. In a study where 100-mm thick steel, it was observed that at relatively low traverse rate where the cut diverges, a negative tilt angle of one degree will reduced on one side of the cut from about 2-mm to less than 0.5-mm deviation. The accuracy of tilting the jet should be in the order of 0.1 degree in order to accurately obtain the desired wall straightness. Observe the other side of the cut which is now more divergent to about 4-mm deviation.

5. SELECTED APPLICATIONS

Tests were performed to determine the feasibility of roughing thick Titanium disc (150-mm) into blades as shown in Figure 12. To obtain optimum geometrical accuracy and surface finish and the minimum cycle time, a sufficiently accurate 5-axis gantry style manipulator and 600 MPa pump pressure were used.

It was found that a sacrificial cut must be made in order to permit removal of the cut slug between the blades. A rough economic analysis suggests that AWJ roughing is highly competitive to the standard milling process due to the fact that no chips are produced and that the produced slugs has residual value. Finishing the part will require milling of less than 0.25 mm off the AWJ-cut surface.

Figure 12: Titanium Blade Roughing with AWJ

A concept of rapid roughing using multi-axis manipulator such as a 6-axis robots is shown in Figure 13. A robot dripped may hold a part and articulate it under a stationary AWJ to near net shape it within the limits of the robot arm and process accuracies. Again, the advantage in this case to minimize chip cutting.

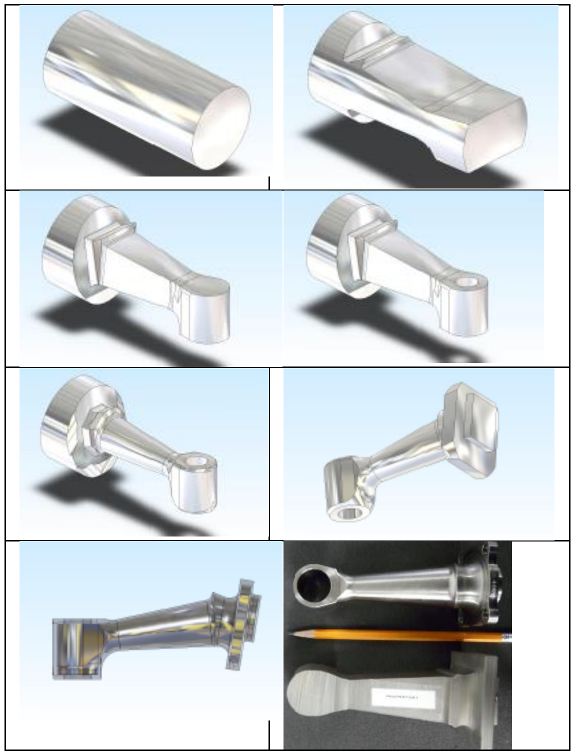


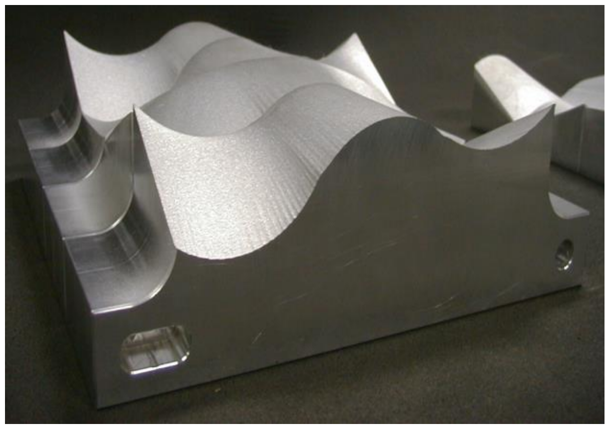
Figure 13: Roughing of Inconel Injector Nozzle

In another example, Figure 14, a large glass block 300-mm deep was light-weighted for a space telescope mirror core by cutting out triangular shapes, leaving about of 2-mm thick struts. Jet lead and taper angles were determined to minimize undercutting and strut thickness variation to less than 0.5-mm. This means that the wall straightness should be within 0.25-mm. One of the challenging tasks for cutting fragile thick materials is handling the cut-outs. Due to their relatively large weight, a weight transfer method must be used. This can be achieved by either clamping the cutout using a simple clamp or using frictional inserts inside the kerf.

	
Hexagonal Honeycomb Shape Cut in Glass	Residual pieces of glass removed from block

Figure 14: Light-weighting of Thick Glass for Mirror Cores

The capability of the abrasive-waterjets for cutting relatively thick sections of steel offers a great potential for rapid fabrication of automotive tooling molds. This process can deliver near net shape tooling in fraction of the time currently being used to cast or rough a mold cavity. This process involves the assembly of an array of uniquely profiled sections of steel to form the mold core or cavity. Also, this method allows for the incorporation of conformal cooling (or heating) passages. The profiling and beveling of each steel section is accomplished with an abrasive waterjet. Figure 15 shows cuts in 100-mm thick aluminum to form a 3-D laminated part to illustrate the concept.



AWJ Cuts for 3-D Laminated Object

Figure 15: AWJ Cuts for 3-D Laminated Object

6. CONCLUSIONS

The following conclusions can be drawn from this work:

- Abrasive-waterjets have been demonstrated for cutting of thick materials such as titanium, glass and steel.
- A certain level of jet power needs to first be determined to cut at the required speeds and surface finish. Jet angulation is then used to overcome kerf taper and undercutting.
- Jet lead angle is the key parameter for reducing the trail-back and the associated undercutting anomalies around corners and tight curves.
- Kerf wall taper can be significantly improved using jet taper angles. For thick materials, this taper angle needs to be accurately controlled to within 0.1 degree
- A simple physical model has been developed and shown to correlate well with experimental data of kerf shape.
- A kerf width model has been proposed in this paper. This model will be tested against experimental kerf width data in a future study.

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