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Paper

BENEFITS OF DYNAMIC WATERJET ANGLE COMPENSATION

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ABSTRACT

Dynamic waterjet (DWJ) angle compensation systems have been introduced to the marketplace. They offer new advantages for producing accurate parts. Before DWJ, the cutting speed was the only one degree of freedom available to control part geometry for a given jet. Now, two additional degrees of freedom, namely taper and lead angles control, are provided with DWJ. By accurately modeling and using taper and lead angles, the productivity can be increased by several factors because the jet may no longer need to be slowed down significantly around corners or to obtain parallel walls. The cutting speed should mainly (or only) be determined by the required surface finish and not by the cut geometry. In this paper, the speed range is divided into zones based on the level of produced waviness and these zones also relate to taper and trailback. Optimal selection of the lead and taper angles is related to waviness, taper, and trailback.

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1. INTRODUCTION

During the early years of AWJ introduction to the industry, the focus was on ease of use and versatility. Now with the AWJ technology maturing and becoming the standard in many industries, demands for higher productivity, accuracy, predictability, reliability, and efficiency are rising. This led to the recent introduction of two critical technologies. The first is raising the pressure from 400 MPa to 600 MPa (1) to increase cutting speed and reduce abrasive consumption. The other is to dynamically use jet angle compensation (2) to improve the accuracy of machined parts at relatively high productivity levels.

There are two basic levels of interest related to AWJ-machined parts. These are:

- Part Geometry: Cutting with beam-like tools like waterjets may result in parts with different geometries at the bottom surface as compared to the top surface. Two basic anomalies result because of the nature of the macro mechanics of the waterjet cutting process. These are:
  - o Wall taper: The cut walls may not be parallel to the jet vector as it emerges for the jet.
  - o Undercut: Cuts around corners may exhibit distortion that increases as depth of cut increases.
- Surface Finish: The surface finish of a waterjet cut can basically be characterized by two features:
  - o Waviness: Waviness occurs due the to macro mechanics of jet penetration. They are the larger level of surface irregularity.
  - o Roughness: This occurs due to micro mechanics of particle impact. Roughness is mainly a function of grit size and the represent the smaller level of surface irregularity.

Figure 1 shows an example illustration of the above phenomena. As shown, the cut finish can be decomposed to waviness and roughness.

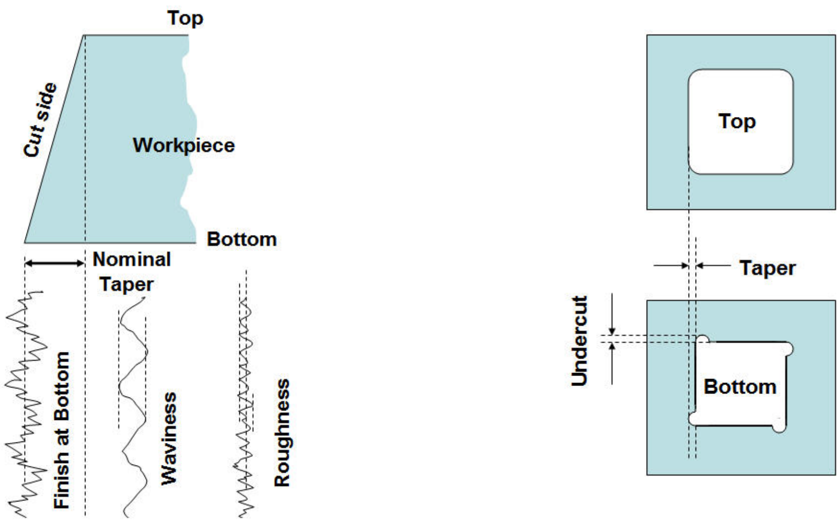

Figure 1: Cut Features Showing Taper, Trailback, Waviness, and Roughness

It is typical that the priorities for producing a part is to first obtain the correct geometry without taper and undercutting. Then the issue of waviness is addressed. Finally, the roughness may become a requirement.

To improve the roughness, a finer abrasive particle size needs to be used. This may, in turn, affect the waviness (due to change in overall jet macro mechanics) if the cutting speed is kept unchanged.

This paper addresses the issue of geometrical accuracy of parts cut with AWJs. More specifically, it addresses the benefits of dynamic angle tilting to obtain geometrically accurate parts. First, we present observations on AWJ cut geometry and follow this with describing a strategy of cutting using angular compensation. Conclusions and recommendations are given at the end of the paper.

2. KERF OBSERVATIONS

In this section, we present data and observations on AWJ-cut kerfs with focus on angular compensation for accurate cutting. First, the kerf width profile will be discussed. This will be followed by discussing surface finish and trailback.

Figure 2 shows cuts made at different cutting speeds in 25.4 mm thick Titanium from 1% to 100% of the maximum cutting speed. The picture shows the top cuts where all are made to a fixed length of about 25 mm. The cuts at the bottom surface are also shown. Observe that the lengths of the cuts are different due to trailback and become shorter as the cutting speed increases. Also, observe that the irregularity (waviness or striations) of the cuts increases as the speed increases. The waviness of the cuts as can be inferred from the bottom kerf shapes show that there is no observable waviness for the first few cuts from 1% to, say, about 20% to 25%. The bottom picture in Figure 4 shows the edge of the sample illustrating the taper obtained at different speeds. It is observed that the taper at slow speed is divergent (negative) as mentioned above and that the taper increases as the speed increases but then starts to decrease again as can also be depicted from the middle picture (bottom surface) in Figure 2.

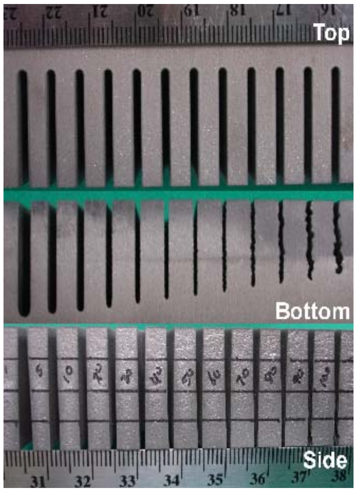

Figure 2: Top, Bottom, and Side Views of Cuts in 1-inch Thick Titanium

2.1 Width Profile

The profile of the different cuts in Figure 2 were measured and plotted in Figure 3. The cutting parameters are also shown in Figure 3 along with the percent cutting speed from 1% to 60%. Observe that the zero taper condition is somewhere between 5% and 10% cutting speeds. Figure 4 shows a plot of taper versus the cutting speed percentage from 1% to 100% cutting speed. Observe that the taper increases as the speed increases unti about 3.26 mm/s (70% cutting speed). The zero taper speed is depicted to be about 0.34 mm/s. A striations-free cut is also observed to be at about 30% cut speed from Figure 2, or about 1.4 mm/s, i.e., 4.1 times the zero-taper cut speed condition.

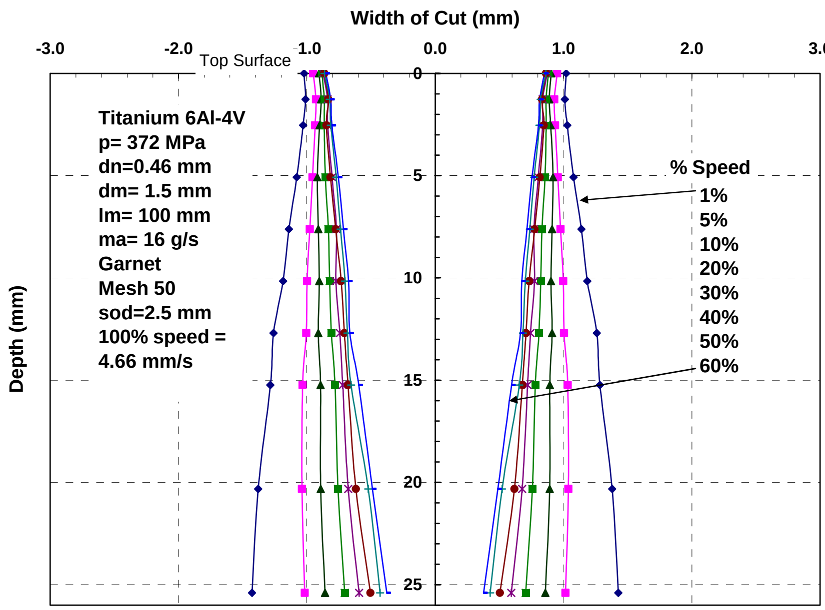

Figure 3: Width of Cut Profiles in 1-inch Thick Titanium

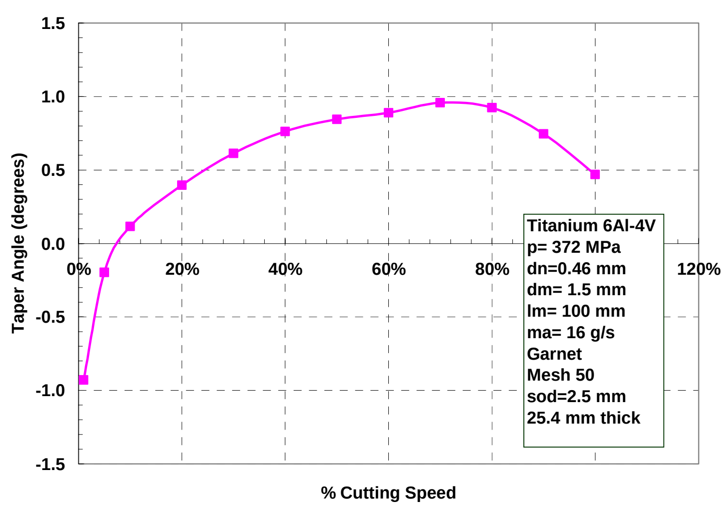

Figure 4: Taper Versus Speed for in 1-inch Thick Titanium

As shown in Figures 2 and 4, the average width of cut at the bottom decreases as cutting speed increases until certain transition speed value after which the width of cut at the bottom increases. This is attributed to the jet becoming unstable with side to side deflections contributing to widening the bottom kerf and making it highly irregular with possible uncut ligaments.

Another example of kerf width profile is shown for 100-mm thick Titanium in Figure 5 at similar conditions to those listed on Figure 3. Observe the barrel shape of the kerf which becomes straighter as the cutting speed increases. Also observe that the top kerf width is slightly larger than the kerf width just below the top surface. This highlights an important feature of AWJ cutting and how taper should be measured. For example, using the top and bottom kerf width to determine taper does not reflect the nature of the cut and may lead to erroneous estimates for selecting the cutting speed or taper angle. The 20% cut in Figure 5 indicated a minimal taper condition based on top and bottom kerf width measurement. However, this cut exhibits a relatively large "bow" around the 38-mm depth level into the material. The 50% cut shows more taper but much less bow. Accordingly, compensating for the taper angle for the 50% cut will result in a more geometrically accurate result. The shown top surface kerf width widening (and rounding) is attributed to the stand off distance and again contribute to errors in estimating the taper angle. The larger the stand off distance, the larger the rounding and kerf width widening will be at the top.

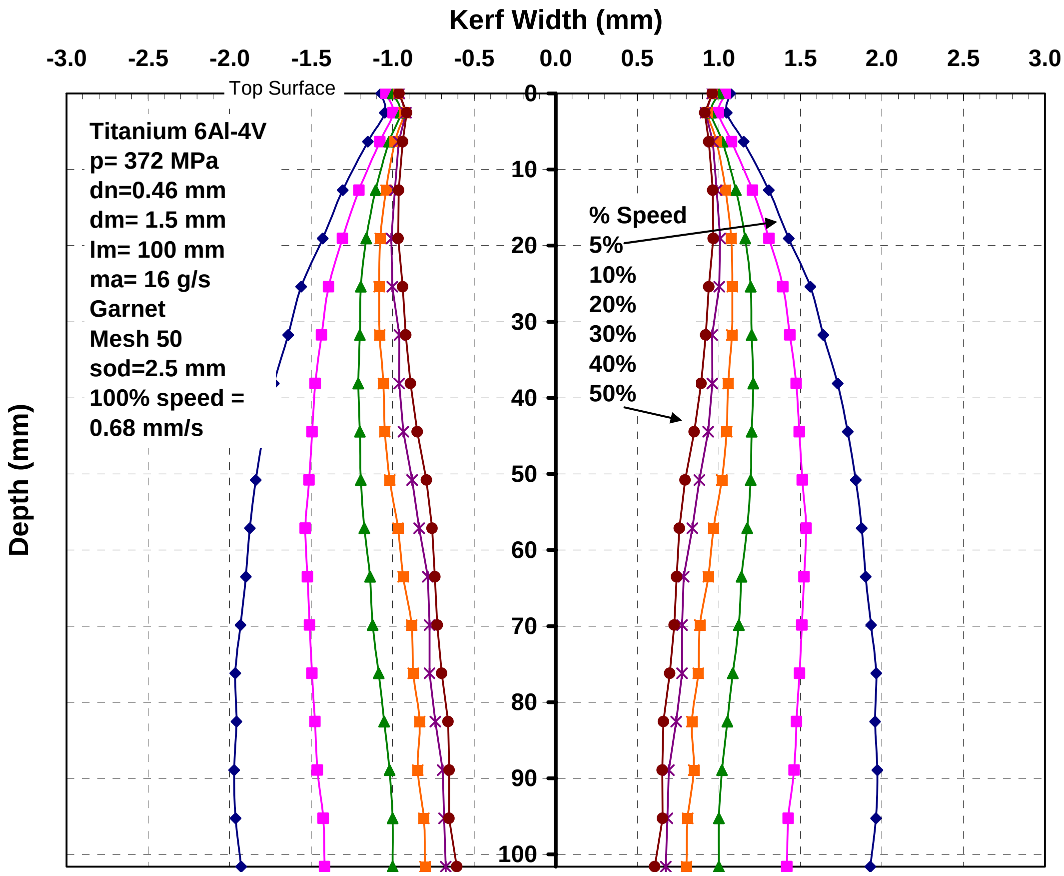

Figure 5: Width of Cut Profiles in 4-inch Thick Titanium

An optimized selection of AWJ nozzle and parameters should then aim at conditions with minimal bow and not minimal taper when the edge quality is acceptable and tilt capability is available.

To correct wall taper, the jet is angled perpendicular to the direction of traverse. This tilt angle is typically small and in the order of 1 degree as shown in Figure 4 above. It is typical that thinner materials require larger taper angles corrections. Figure 6 shows that tilting the jet at 0.2 degree will improve wall taper for the 50% cut speed shown in Figure 5 above. A taper of about 0.4 mm was reduced to about 0.1 mm on one side of the cut.

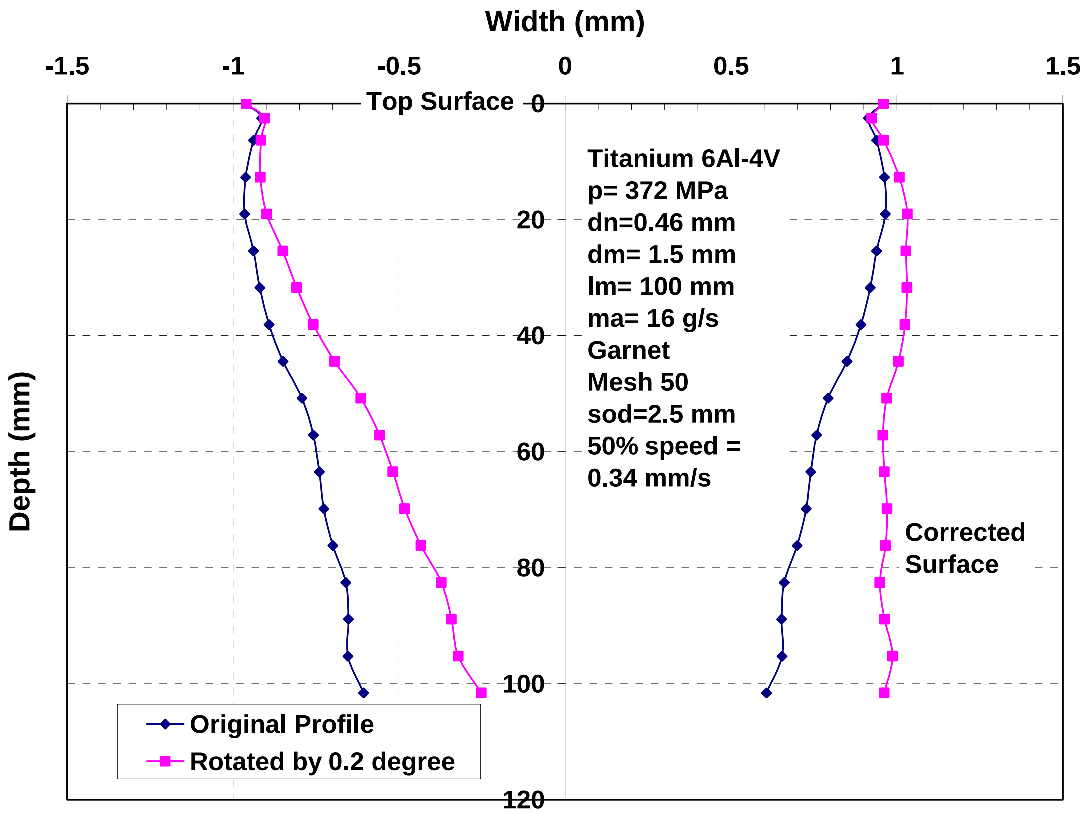

Figure 6: Reduced Surface Taper By Angular Compensation

2.2 Waviness

An AWJ cut surface is mainly characterized by at least two surface measurements (3). These are roughness and waviness. Roughness is mainly affected by the abrasive particle size and is attributed to the micro mechanics of abrasive particle impact. Waviness is a beam cutting phenomenon and it is the more dominant characteristic that affects the selected cutting speed. It is mainly attributed to the macro mechanics of jet penetration which can also be affected by the steadiness of the AWJ process dynamic parameters. Figure 7 shows typical surfaces produced with an AWJ. The surface finish varies from top to bottom and typically transition from a rough surface to a wavy surface, the slower the traverse rate, the larger the non-wavy surface zone. Hashish model for surface waviness (4) suggested that the waviness does not exist for cuts of zero or negative taper and the surfaces may then be characterized by roughness only. However, waviness may also not be observed for cuts with slightly positive taper. Other studies on surface modeling indicated the complexity of the surface, factors affecting it and its multiple zones (5-7)

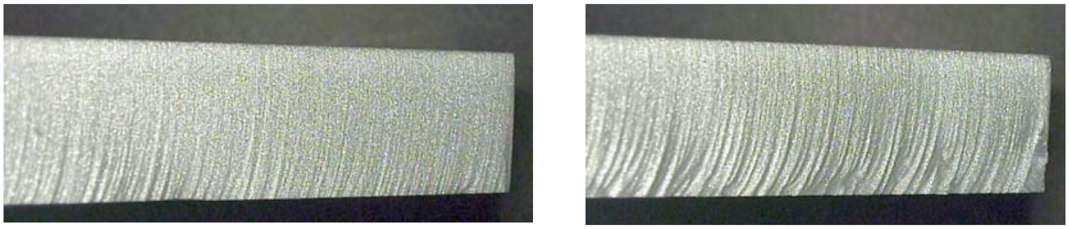

Figure 7: Typical AWJ Surface Topography

Figure 8 shows the effect of speed on waviness measured at the bottom of the cut. It is interesting to notice that when the cutting speed is normalized to the maximum cutting speed, the data collapses on a common trend line. Observe that the speed range can be divided into three zones. In zone 1, no waviness may be observed. In zone 2, slight waviness may be observed and it increases with speed increase at a relatively slow linear rate. A higher rate of increase in surface waviness characterizes zone 3 which can also be somewhat linear. The range of speed form, say 50% to 70%, is a transition zone.

The peak-to-valley waviness may approach the same level of taper. In this case, the waviness may be considered to calculate the taper correction angle. Two scenarios may be used to calculate the taper angle either relative to the mean waviness location or to the root waviness location. In the second case, the wavy surface may be removed with a secondary finishing process leaving a surface with zero taper.

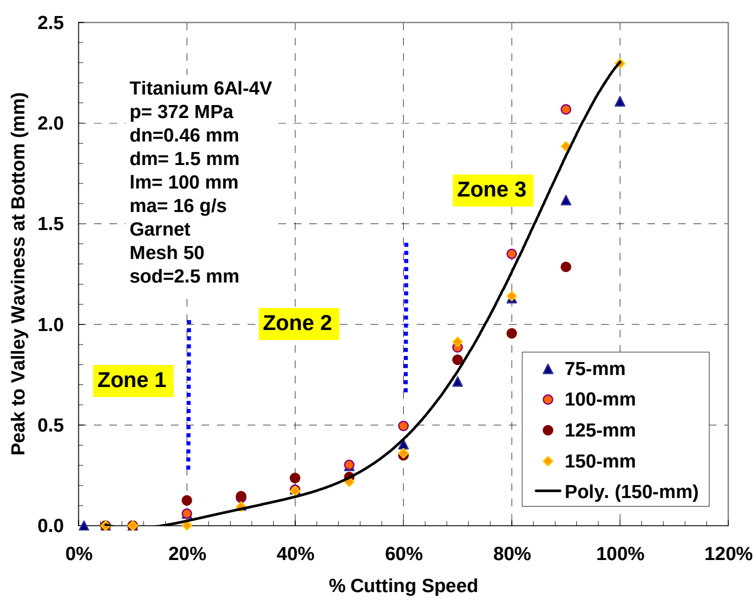

Figure 8: Effect of Speed on Surface Waviness

2.3 Trailback

Figure 9 shows trialback curves as a function of speed for 150-mm thick titanium. Observe that the trailback curve is parabolic in nature. 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 (8-9) have also addressed trailback curve shape.

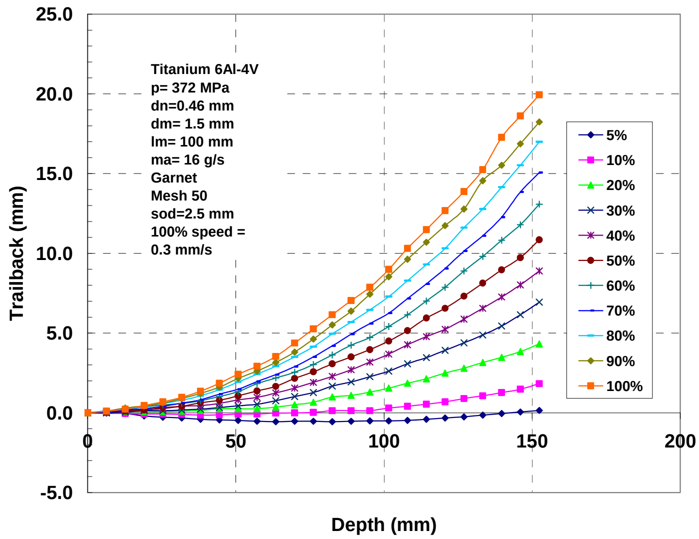

Figure 9: Trail-back Geometry for Several Cuts in Titanium

The effect of speed on the maximum trailback at the bottom of the cut is shown in Figure 10 for 25-mm and 100-mm thick Titanium. Observe that the trailback increases linearly with increasing speed.

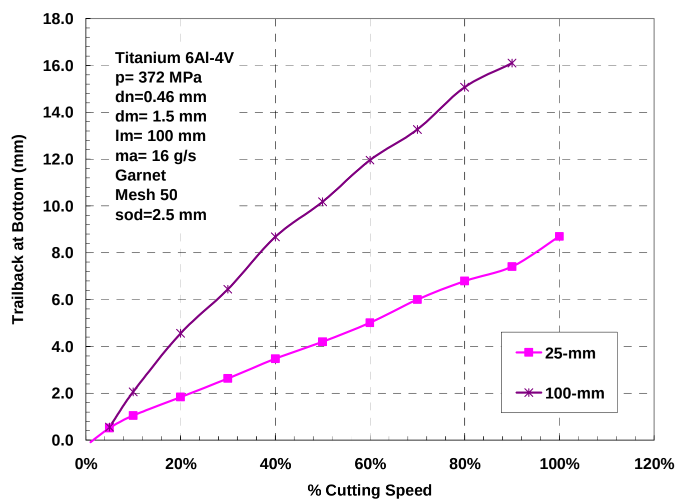

Figure 10: Effect of Speed on Trailback at Bottom

In order to minimize the effect of trailback on the cut geometry, jet angling with a lead angle will be needed. Figure 11 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 trailback occurs near the middle of the part thickness. The amount of this trailback is about 4-mm at this angle versus 17-mm when no lead angle is used. This dramatic reduction in trailback 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 trailback can be reduced to nearly zero when the appropriate lead angle is used. This is of critical importance when machining precise parts.

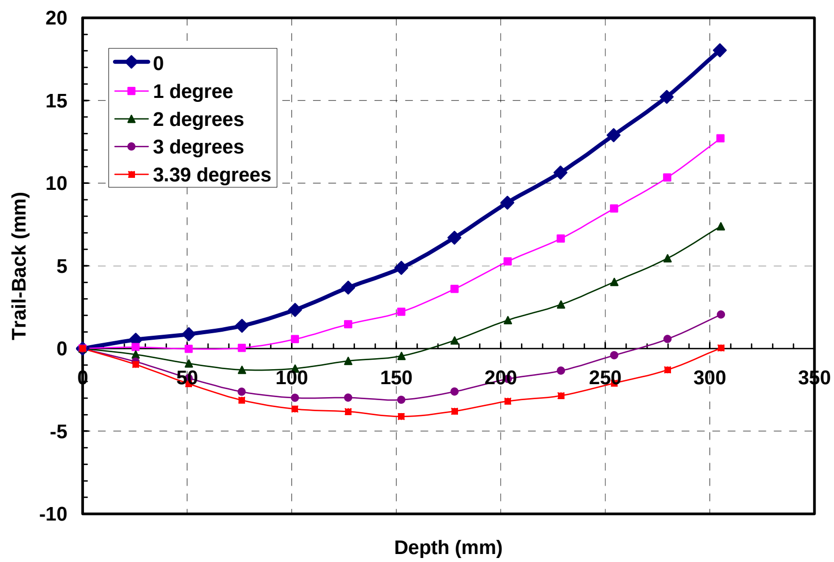

Figure 11: Effect of Lead Angle on Kerf Shape and Trailback

3. ANGULAR COMPENSATION

The general trend of taper, trailback and surface finish as functions of speed is illustrated in Figure 10. This figure shows general speed zones separated by four critical cutting speeds. The first critical cutting speed u1 is the one at which zero taper occurs. Slower speeds than u1 will result in divergent cuts with negative taper and no waviness. The second critical cutting speed u2 characterizes the beginning of waviness formation. Increasing the speed beyond u2 will continue to increase taper to a maximum value at the third critical speed u3. Beyond u3, the taper will decrease and the surface will be highly wavy and irregular. At speed u4, the jet will barely cut through the material not cut through completely.

The cut surface at speed slightly below u_2 will produce a waviness-free surface similar to, but slightly rougher, than that obtained at speed u_1. Usually u_2 is several times faster than u_1.

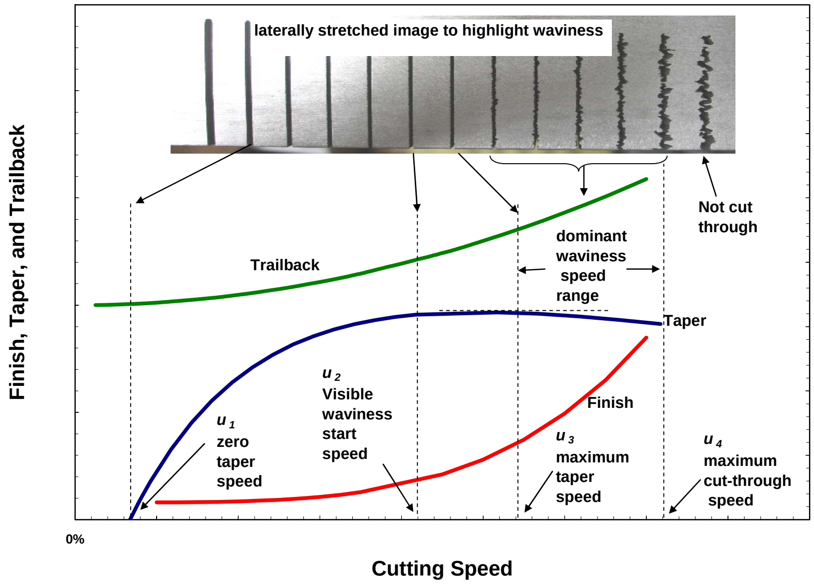

Figure 12: General Cutting Speed Zones

To capitalize on the dynamic waterjet angle tilting capability, the cutting speed can be maximized based on the required surface finish regardless of taper (and trailback). In this case, taper angles are used to obtain the required part accuracy by correcting the wall taper on the required side of the cut. Assume that an acceptable surface finish is Ra. This will identify a cutting speed u_f. The taper obtained at this speed is then determined as shown in Figure 20. This will define a taper angle to be used. The same applies for trailback.

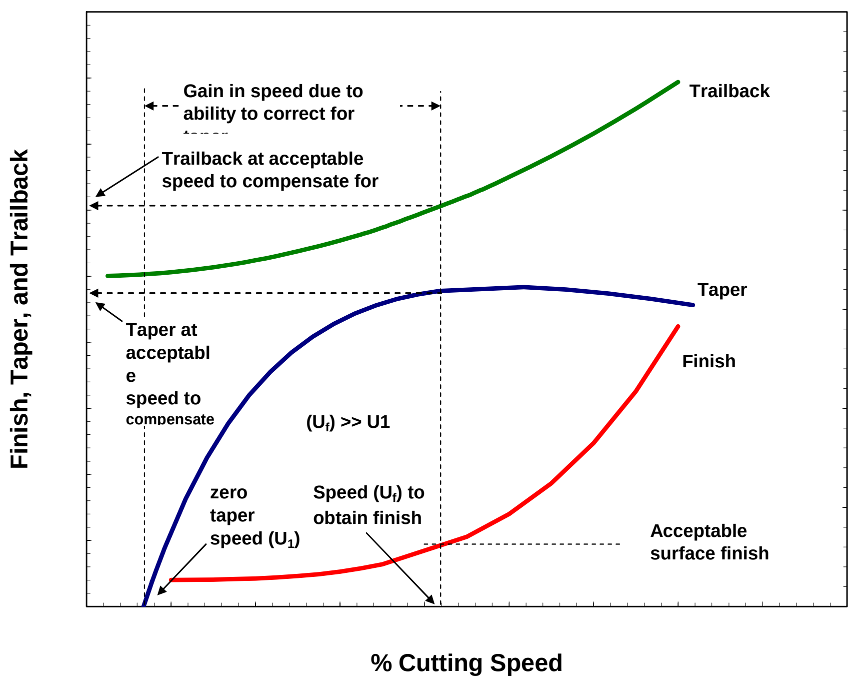

Figure 13: General Cutting Speed Zones

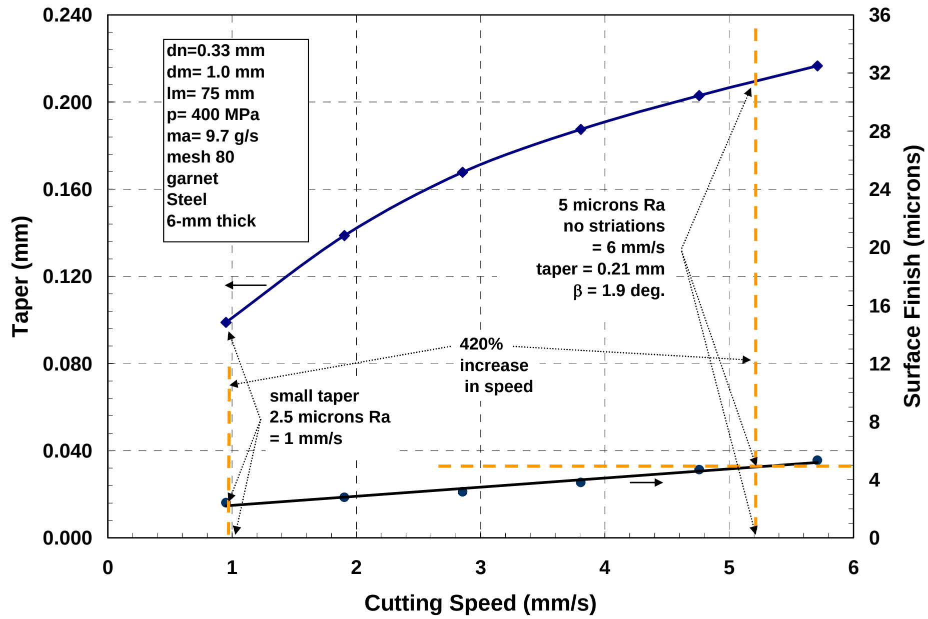

Figure 14: Example Speed Improvement due to Angular Compensation

4. CONCLUSIONS

The following conclusions can be drawn from this work:

- The accuracy of AWJ-machined parts can be improved using dynamic angular compensation without having to slow down the jet. The required surface finish can be the only factor that determines the cutting speed.
- Jet lead angle is the key parameter for reducing the trailback 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.
- Using dynamic waterjet angle compensation with its full potential will increase productivity by several factors for cutting accurate parts in comparison to non-compensated cases.
- The speed range from 0% to 100% of maximum cutting speed has been divided into zones relating waviness to taper and trailback. Optimizing these three attributes will be needed to obtain most accurate results and highest productivity.
- The shape of the kerf wall sides and front is as critical as the taper and trailback values defined by their top and exit parameters. This shape, at the selected speed, depends on the other jet parameters.
- The use of the maximum cutting speed as a characteristic normalizing speed parameter is a promising approach for data reduction, and modeling. Further work is needed in this area.

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