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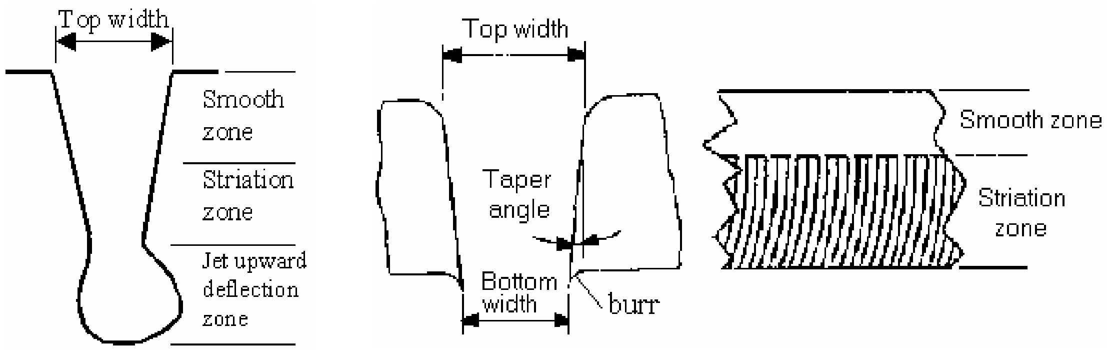
Abstract. An analysis of the effect of jet impact angle on the major cutting performance measures in abrasive waterjet (AWJ) machining of alumina ceramics is presented based on experimental investigations. It is found that angling the jet forward in the cutting plane is an effective means in improving the cutting performance. A quantitative assessment is made which shows that the optimum jet impact angle for cutting alumina ceramics is about 10^{o}. Further improvement on the cutting performance can be made by using the optimum jet impact angle in multipass AWJ cutting.

Introduction

Abrasive waterjet (AWJ) cutting is one of the most recently developed manufacturing technologies. It uses a fine water and abrasive slurry jet to cut the materials by means of erosion. This cutting technology has various distinct advantages over the other cutting technologies, such as no thermal distortion on the workpiece, high machining versatility to cut virtually any material, high flexibility to cut in any direction, and small cutting forces [1]. As a result, it is being increasingly used in the manufacturing industry. However, many aspects of this technology have not yet been fully understood and its cutting capacity has limited its applications to relatively thin materials and where the requirements for the kerf quality are not high.

Over the last decades, numerous research and development efforts have been made to study this cutting technology. It has been found that the surfaces produced by an AWJ consist of an upper smooth zone where the surface is characterized by surface roughness and a lower rough zone where the surface has wavy striations, as shown in Fig. 1. It has been claimed [2-5] that the upper smooth zone is a result of jet attack at shallow angles where the material is removed by the cutting wear mechanism, while the striated surface is produced by the jet at large angles of attack whereby the deformation wear mechanism applies to the material removal. The attack angle is defined as the angle between the jet flowing direction and the surface under the jet attack. For non-through cuts, a large pocket is formed at the kerf bottom because of the jet upward deflection. The geometry of the kerf generated by an AWJ is characterized by a wider entry at the top than the exit at the bottom so that a taper is produced. There may be a round corner at the top kerf edges because of the water bombardment and burrs at the exit kerf edges for through cuts of ductile materials as a result of the material plastic deformation, as shown in Fig. 1.

Various attempts have been made to increase the cutting performance of AWJ, such as the total depth of cut, the depth of upper smooth zone (or smooth depth of cut) and the surface finish. These studies include the use of multipass operations [6,7] and nozzle oscillation cutting technique [2,8,9]. These cutting techniques have been found to be very effective in increasing the AWJ cutting performance without additional costs to the cutting process. It can be noticed from Fig. 1(c) that as the abrasive particles cut into the workpiece, the direction of cutting changes as indicated by the particle traces or drag angles on the cut surface. This change in the cutting direction reduces the component of energy for removing the material. It is thus suggested that a jet forward impact angle in the cutting plane may be introduced to compensate for this drag angle so as to improve the cutting performance, where the jet impact angle is defined as the angle between the initial jet flowing direction and the workpiece surface. Changing the jet impact angle will ultimately change the jet attack angle on the target materials and affect the mode of erosion. Some investigations into this cutting approach have been reported [4,10] and shown that changing the jet forward angle is an effective means in improving the cutting performance without any negative effects and can be realised in almost all waterjet cutters in use. However, it has been claimed that the optimum jet impact angle is dependent on the properties of work material being processed. Further, it is not well documented the quantitative improvements on the cutting performance that can be achieved by using jet impact angle in AWJ machining.



(a) Non-through cut (b) Through cut (c) Surface properties

Fig. 1. Schematic of AWJ produced kerf profile and surface.

In this paper, an experimental investigation will be conducted to assess the effect of jet impact angle in AWJ machining of an alumina ceramic. From a study of single pass cutting, the optimum jet impact angle will be determined and the quantitative improvement on the cutting performance by using the optimum jet impact angle will be reported. A further analysis will be made to assess the effect of jet impact angle on the cutting performance in multipass AWJ machining.

Effect of Jet Impact Angle in Single Pass Cutting

Experiment. The experiment was conducted on a Flow System International waterjet cutter that was equipped with a model 20X dual intensifier high output pump (up to 380 MPa or 55,000psi) and a five axis robot manipulator for positioning the cutting head (or nozzle). A nozzle of 1.02 mm in diameter and 76.2 mm long and an orifice diameter of 0.33 mm were used for the cutting tests with 80 mesh almandine garnet sand as the abrasive material. The specimens were 87% alumina ceramic titles of 12.7mm and 25.4mm thick; some major properties of the specimens are given in Table 1. A wide range of the major and easy-to-adjust cutting variables as identified in earlier studies [2,4] were considered and an S-Plus statistical package was used to assist in the experimental design. These variables included the water pressure (from 290 to 380 MPa), nozzle traverse speed (from 0.67 to 2.33 mm/s), abrasive mass flow rate (from 6.67 to 11.67g/s), and the standoff distance between the nozzle and workpiece surface (from 2 to 6 mm). The nozzle was tilted in the cutting plane to change the jet impact angle from 60^{o} to 90^{o} with a 5^{o} increment, in which 90^{o} represented the orthogonal cutting situation where the nozzle was perpendicular to the workpiece surface; while the angles of less than 90^{o} were for the nozzle to tilt forward with respect to the nozzle traverse direction.

Table 1. Major properties of the 87% alumina ceramics.

Hardness (Rockwell C)	79	Flexure strength (MPa)	336
Average crystal size (μm)	2-10	Tensile strength (MPa)	221
Compressive strength (MPa)	2480	Modulus of elasticity (GPa)	276

Effect on Cutting Performance. Fig. 2 shows the effect of jet impact angles on the depth of cut (or depth of jet penetration) and smooth depth of cut in the upper zone. It can be seen from Fig. 2(a) that the depth of cut increases significantly as the jet impact angle increases from 60° to 80°. For almost all the test cases, a further increase in the jet impact angle to beyond 80° has resulted in a decrease in the depth of cut. The optimum jet impact angle is about 80°, i.e. the nozzle titled forward at about 10° in the cutting plane, as shown in Fig. 2 where V is the jet traverse speed. It appears that this optimum value is independent of other variables used in this study. Using this optimum jet impact angle can considerably increase the depth of jet penetration comparing to the orthogonal cutting situation; in many cases more than 20% of increase was produced.

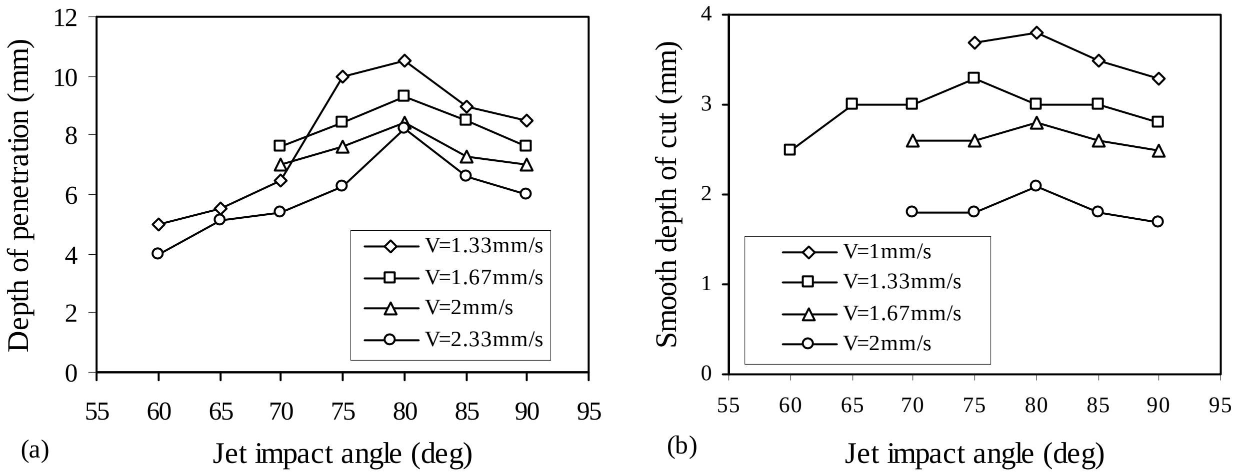


Fig. 2. Effect of jet impact angle on cutting performance (standoff = 5mm, water pressure = 350MPa, abrasive flow rate = 11.67g/s).

This increasing depth of cut is attributed to the distribution of the particle energy as the jet angle varies, whereby the jet impact angle compensates for the jet drag angle in the lower cutting region so that the tangential component of the particle energy is increased. This increase is particularly crucial when the jet energy is about the threshold value for cutting the material. As a result, the total jet penetration is increased. However, a further reduction in the jet impact angle will not only reduce the cutting effectiveness in the upper but also in the lower cutting region due to over compensation. Therefore an optimum jet impact angle exists.

It follows from the above analysis that the jet impact angle does not affect the smooth depth of cut in the upper region as significantly as for the depth of jet penetration. This is shown in Fig. 2(b). Nevertheless, a considerable improvement in the smooth depth of cut can be made by using an optimum jet impact angle which is about 75° to 80°. In some cases, using the optimum jet impact angle can result in more than 10% increase in the smooth depth of cut, typically about 15% when 80° jet impact angle is used instead of 90°. Consequently, 80° may be considered as the optimum jet impact angle for these two major cutting performance measures.

The analysis of the surface roughness was based the center-line average R_a values measured at about 3 mm from the top kerf. The results showed that the minimum R_a occurred when the jet impact angle was between 70° and 90° in which the R_a value was marginally smaller than those at smaller jet impact angles. This trend is consistent with the finding reported by Hashish [10] and is due to the fact that at large jet impact angle, the increase in the tangential component of particle energy results in an increase in the 'cutting wear' mode erosion, which reduces the surface roughness. It appears that within 70° to 90° of jet impact angle, the variation of surface roughness is not discernible where the variation of R_a is within 0.5μm.

It was found from the tests that jet impact angle had no discernible effect on the top kerf width. This trend may be anticipated since the kerf width is highly dependent on the properties of the material and the jet structure (i.e. the effective diameter) [4,11]. A similar trend was also noticed for kerf taper; this is again because the jet structure or energy distribution determines the kerf width while the jet impact angle has little effect on it. Thus, from the above study 80^ocan be used as the optimum jet impact angle for cutting 87% alumina ceramics.

Effect of Jet Impact Angle in Multipass Cutting

Experiment. The cutting tests were conducted on the same machine with the same cutting head configurations as for the single pass cutting tests. The abrasive material was 80 mesh almandine garnet sand and its mass flow rate was 8.33 g/s. A single level of standoff distance at 4 mm was used for all the tests on 87% alumina ceramic tiles of 25.4mm thick.

Based on the foregoing single pass cutting study, a jet impact angle of 80^o was used at different combinations of nozzle traverse speeds, as given in Table 2, and at a single level of water pressure (345 MPa or 50,000 psi). To facilitate the comparisons, these traverse speed combinations were also tested at a 90^o jet impact angle. These tests enabled to study the benefits of using both multipass cutting and angling the jet. The jet traverse directions for all passes were kept the same.

Table 2. Combinations of traverse speeds used in the tests (jet impact angle = 80^o and 90^o).

Jet traverse	Combinations of jet traverse speeds										
speed [mm/s]	1	2	3	4	5	6	7	8	9	10	11
V_1	0.67	0.67	0.67	0.67	0.67	0.67	1.33	1.33	1.33	1.33	1.33
V_2		0.67	0.67	1.33	1.33	2.67		1.33	1.33	2.67	2.67
V_3			0.67		1.33	2.67			1.33		2.67

Table 3. Total depth of cut d_t and smooth depth of cut d_s at different jet impact angles.

	Jet traverse speed			90^o impact angle		80^o impact angle		% increase of 80^o with respect to 90^o	
Sample No.	V_1 [mm/s]	V_2 [mm/s]	V_3 [mm/s]	d_t [mm]	d_s [mm]	d_t [mm]	d_s [mm]	d_t inc.	d_s inc.
1	0.67			17.42	4.96	19.33	5.53	11.0	11.5
2	0.67	0.67		-	7.50	-	8.33		11.1
3	0.67	0.67	0.67	-	8.72	-	9.66		10.8
4	0.67	1.33		-	6.78	-	7.43		9.6
5	0.67	1.33	1.33	-	7.62	-	8.31		9.1
6	0.67	2.67	2.67	-	6.64	-	7.56		13.9
7	1.33			11.73	3.63	13.09	4.47	11.6	23.1
8	1.33	1.33		20.23	5.68	-	6.50		14.4
9	1.33	1.33	1.33	-	6.50	-	7.10		9.2
10	1.33	2.67		15.92	5.01	23.04	5.68	44.7	13.4
11	1.33	2.67	2.67	24.42	5.68	-	6.43		13.2

"-" Indicates through cuts, specimen thickness = 25.4 mm.

Effect on Cutting Performance. By comparing the various cutting performance measures at 80^o and 90^o jet impact angles, it was found that the jet impact angle did not result in significant change in the top kerf width and kerf taper, as was the case in single pass cutting mentioned earlier.

The effect of jet impact angle on the total depth of cut and smooth depth of cut is shown in Table 3. It is apparent that the benefit of angling the jet forward in the cutting plane can again be achieved in multipass AWJ cutting. For all the cases, the use of 80^o jet impact angle clearly shows the advantage in increasing these two cutting performance measures. Analyzing the multipass cutting results, the 80^o jet impact angle has resulted in as high as 45% increase in the total depth of cut for the test conditions in this study as compared to the corresponding multipass cutting with 90^o jet impact angle, while the increase in the smooth depth of cut ranges from about 9% to 23%. When comparing to single pass cutting with the same total cutting time, the use of 80^o jet impact angle and multipass cutting mode can result in more than 30% increase in the smooth depth of cut from this study. Fig. 3(a) shows how the combination of multipass cutting and using 80^o jet impact angle can be employed in the situations where a large smooth depth of cut is required.

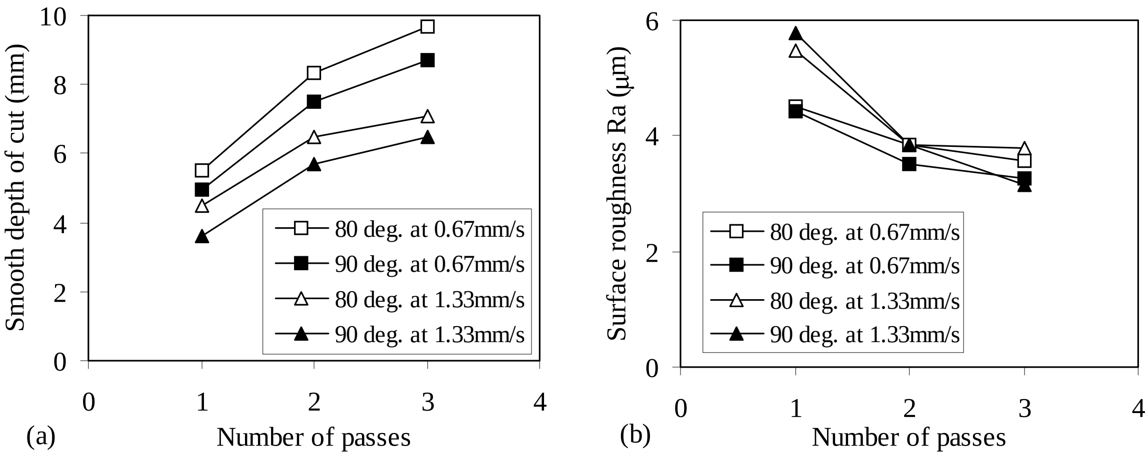


Fig. 3. Effect of jet impact angle in multipass cutting at different traverse speeds.

As this work was not intended to study the surface roughness variation along the kerf wall, the surface roughness (center-line average R_a) values were obtained at about 2 mm from the top kerf edge for analysis. An examination of the experimental results has revealed that the 80^o jet impact angle did not make a noticeable effect on the surface roughness as compared to those at 90^o jet impact angle. This finding is consistent with that from the study on single pass cutting as mentioned earlier.

Conclusions

A study of the effect of jet impact angle on the major cutting performance measures has been presented when AWJ cutting of alumina ceramics in both single- and multi-pass cutting modes. It has been confirmed that the optimum jet impact angle for cutting alumina ceramics is about 80^o. This jet angle can considerably increase the depth of cut by up to more than 20% in single pass cutting when comparing to those with a 90^o jet impact angle. It can also improve the smooth depth of cut by up to 15% in most cases. However, the other cutting performance measures and kerf characteristics had no discernible difference when 80^o and 90^o jet angles were used. The benefit of using the optimum jet impact angle can further be achieved when multipass cutting mode is used where the increases in the total depth of cut and smooth depth of cut are significant when comparing these quantities produced by 80^o and 90^o jet impact angles.

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