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An experimental study to enhance the cutting performance in abrasive waterjet machining

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ABSTRACT

An experimental study to enhance the cutting performance in abrasive waterjet (AWJ) machining is presented. The study uses the techniques of jet forward impact angles and multipass operations both individually and concurrently when cutting an alumina ceramic and a polymer matrix composite. A brief report on the effect of jet impact angle in single pass cutting is made first, which shows that the optimum jet impact angle for both the ceramics and polymer matrix composite is about 80^o. It is found that the multipass cutting technique can increase the cutting capability and application domain of AWJ cutting. It can also improve the major cutting performance such as the depth of cut as compared to single pass cutting within the same total cutting time. The benefit of using multipass cutting operations is further enhanced when it is combined with a jet forward angle of 80^o in cutting alumina ceramics.

Keywords: abrasive waterjet cutting, multipass cutting, cutting performance, machining

1. INTRODUCTION

Abrasive waterjet (AWJ) machining is one of the most recently developed non-traditional manufacturing technologies. It uses a fine jet of ultrahigh pressure water and abrasive slurry to cut material by means of erosion. It 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, this technology has found extensive applications in manufacturing industry [2,3]. It has been particularly gaining favour in cutting “difficult-to-cut” materials such as ceramics [4-9], and layered composites [9-15] as well as in pattern cutting on various materials. However, its cutting capacity has limited its application, particularly for processing thick materials and in the cases where the requirements for the kerf quality and surface finish are high.

In this paper, a study to use jet forward impact angles and multipass operations to enhance the cutting performance in AWJ machining is presented. Because of the increasing applications of ceramics and composites in industries and the difficulties and low productivities in processing these kinds of materials by other techniques such as sawing and diamond sawing, the study will be focused on cutting an 87% alumina ceramic and a polymer matrix composite. Multipass operations are conducted in such a way that a water jet travels over the same kerf for more than one times (i.e. multiple passes). The experimental results are analyzed to assess the effect of these cutting techniques, when used individually and concurrently, on the cutting performance. This analysis will form a guideline for process design and the selection of cutting conditions in AWJ machining. To facilitate the analysis, a brief review on the previous investigations is given first.

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2. KERF CHARACTERISTICS AND PREVIOUS INVESTIGATIONS

Since the introduction of AWJ cutting technology, a large amount of research effort has been directed to exploring its applications and the associated science [2,16]. It has been found [4,17] that three cutting zones exist in the processing of ductile and brittle materials under an AWJ, i.e. a cutting zone at shallow angles of attack, a cutting zone at large angles of attack, and a jet upward deflection zone. The attack angle is defined as the angle between the jet flowing direction and the surface under the jet attack. The study on layered materials such as polymer matrix composites [13,14,15] has revealed similar phenomenon in terms of the cutting zones. Based on the proposals by Bitter [18] and Finnie [19] for particle erosion of materials, Hashish [17] claimed that the cutting mechanisms in the first two zones could be considered as cutting wear and deformation wear, respectively, while in the third zone the cutting process is considered as being controlled by erosive wear at large particle attack angles [4]. Furthermore, 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. In the jet upward deflection zone (for non-through cuts only), a large pocket is formed. Research is still being undertaken to gain a full understanding of the mechanism of striation formation in order to reduce or eliminate its formation. 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 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.

<take in Fig. 1>

A large amount of research has been carried out to understand and improve the AWJ cutting performance, such as the kerf taper, surface roughness and striation, material removal rate and depth of cut or jet penetration. This includes the study of the dynamic characteristics of the jet [20-22], and the analysis of machined surfaces and kerf geometrical features to optimise the cutting process [6, 13, 17, 23-25]. It is now evident that there are numerous cutting variables that affect the cutting performance of an AWJ. The most dominant parameters have been identified and considerable research has been directed towards the effects of these dynamic and easy-to-adjust parameters, which include water pressure, nozzle traverse speed, standoff distance between the nozzle and workpiece, and abrasive material, size and mass flow rate. In general, it has been found [13, 26] that an increase in water pressure and abrasive mass flow rate and a decreases in nozzle traverse speed and standoff distance result in an increase in the depth of cut and smooth depth of cut and a decrease in kerf taper and surface roughness. However at higher range of water pressure and abrasive flow rate, the rate of improvement on the cutting performance as either of these two variables increases is reduced, comparing to that at their respective lower range. It has also been found that water pressure and nozzle traverse speed are more dominant in affecting the depth of jet penetration and the depth of upper smooth zone than abrasive mass flow rate and standoff distance [4,27]. Based on these studies, recommendations have been made for selecting the optimum cutting parameters for the materials under consideration.

Consequently, in order to increase the depth of cut (or depth of jet penetration) and the smooth depth of cut as well as to reduce the kerf taper and surface roughness, low jet traverse speeds are normally selected at high water pressures. Such combinations of the process parameters are not preferred in practice from an economic point of view. In addition, the capability of the AWJ cutting technology has limited its application to relatively thin materials and where cut quality requirements are not high. For these reasons, various attempts have been made to increase the cutting performance of AWJ, such as the use of jet forward angles [4,13,28], multipass operations

[20,29] and nozzle oscillation cutting techniques [4,30,31,32]. These cutting techniques have been found to be very effective in increasing the AWJ cutting performance without additional costs to the cutting process. This work presents a study to enhance the cutting performance using the techniques of multipass AWJ cutting and jet forward impact angles, including combining the two techniques. A study of the effect of jet impact angle on the cutting performance in single pass operations is considered before the study of multipass cutting incorporating the optimum jet impact angles.

3. EFFECT OF JET FORWARD ANGLE IN SINGLE PASS CUTTING

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 of particle 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. To assess the effectiveness of this cutting technique and to optimize the cutting parameters, a study has been carried out on cutting an alumina ceramic and a polymer matrix composite that are increasingly used in various applications.

The experiment was conducted on a Flow International waterjet cutter that was equipped with a model 20X dual intensifier high output pump (up to 380 MPa) and a five axis robot positioning system. 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. The abrasive material used was 80 mesh almandine garnet sand.

In the cutting tests on ceramics, 87% alumina ceramic titles of 12.7 mm and 25.4 mm thick were processed. A wide range of the major and easy-to-adjust cutting variables as identified in earlier studies [26,27] were considered, they were the water pressure (from 290 to 380 MPa), nozzle traverse speed (from 0.25 to 0.83 mm/s), abrasive mass flow rate (from 9.6 to 15.2 g/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 100^o with a 5^o increment, in which 90^o represented the orthogonal cutting situation where the nozzle was perpendicular to the workpiece surface; the angles of less than 90^o were for the nozzle to tilt forward with respect to the nozzle traverse direction, while those greater than 90^o were for angling nozzle backward.

The study on composite materials was to cut a phenolic fabric polymer matrix composite which was non-metallic laminated sheets made by impregnated layers of fibre (cotton) reinforcement with resin matrix. The specimens were 300×300 mm squares of 20 mm thick. The cutting conditions were: water pressure = 280, 330 and 380 MPa, traverse speed = 16.67, 26.67 and 36.67 mm/s, standoff distance = 4 mm, and the abrasive mass flow rate = 10 g/s. For each combination of these conditions, the jet impact angle was varied from 50^o to 90^o with a 10^o increment.

The linear measurements (kerf widths and depths) were conducted under a Sigma Scope 500 Profile Projector which amplified the measurands by about 20 times and had digital readouts to an accuracy of 0.001mm. The surface roughness was measured by a Taylor-Hobson Surtronic 3+ stylus profilometer. The centre-line average measure R_a was used with a cut-off of 2.5 mm. All the experimental data were an average of three measurements at different locations on a specimen.

The results for cutting alumina ceramic tiles showed that jet impact angle had an significant effect on the depth of cut while its optimum value was found to be about 80^o to 85^o, i.e. the nozzle titled forward at about 5^o to 10^o in the cutting plane, as shown in Fig. 2 where V is jet traverse speed, P is water pressure and M_a is abrasive mass flow rate. The results showed that the cutting variables within the ranges used in this study did not affect the value of the optimum jet impact angle. Using the optimum impact angle could improve the depth of cut by nearly 30% as compared to that at 60^o jet impact angle, or about 8% if compared to that at the orthogonal cutting condition. It was also found that with a jet impact angle of about 70^o to 75^o, the drag angle in the lower cutting zone of cut surfaces was diminished to almost zero. The experimental results in this study showed that jet impact angle did not have any significant effect on the other kerf characteristics.

<take in Fig. 2>

Fig. 3 shows the effect of jet impact angles on the depth of cut and surface roughness when cutting the polymer matrix composite. It can be seen from Fig. 3(a) that the depth of cut increases by up to about 25% as the jet impact angle increases from 50° to 80^o. It can also be noticed that the rate of the increase is reducing as the jet impact angle increases. For the vast majority of the tests, a further increase in the jet impact angle to beyond 80^o has resulted in a decrease in the depth of cut whose peak values occurred at about 80° of jet impact angle. This increasing depth of cut may be attributed to the fact that a jet impact angle of less than 90^o compensates for the jet drag angle in the lower cutting region, so that the component of the particle energy in the cutting direction is increased, which in turn increases the depth of jet penetration. However, a further reduction in the jet impact angle to less than 80^o will not only reduce the cutting effectiveness in the upper but also in the lower cutting region due to an over compensation. Therefore an optimum jet impact angle exists.

It follows from the above analysis that the jet impact angle does not affect significantly the smooth depth of cut in the upper region within the range tested. By contrast, it results in a marked improvement (up to 50% reduction) in the surface roughness when it increases from 50° to 70°, as shown in Fig. 3(b). This increasing trend vanishes as the jet angle further increases to 90°. This is consistent with the finding reported by Hashish [28] and is due to the fact that at a small jet impact angle, the reduction in the tangential component of particle energy results in a significant change in the ‘cutting wear’ mode erosion, which increases the surface roughness.

<take in Fig. 3>

It was found from the tests on polymer matrix composite that there was a variation of only about 0.1 mm on the top kerf width when the jet impact angle was increased from 50° to 90°. Hence, the top kerf width may be considered as independent of jet impact angle. This trend may be anticipated since kerf width is highly dependent on the properties of the material and the jet structure (i.e. the effective diameter) [13,23]. 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.

This study has confirmed that a jet impact angle of about 80^o can be employed to increase the depth of cut by up to 8% in cutting alumina ceramics when comparing to cutting with a 90^o jet impact angle. However, when cutting the polymer matrix composite, the improvements for the depth of jet penetration and surface finish are marginal when using an 80^o rather than 90^o jet impact angle. For both materials, the jet impact angle was not found to have any significant effect on the other cutting performance measures. In addition, the study on cutting polymer matrix composite has found that when the jet could not cut through the material, delamination defects often occurred whereby there were cracks and bonding failures between layers of the material. Therefore, cutting process should be designed such that the jet can cut through the material in one pass. The predictive depth of cut models such as that in [33] may be used for this purpose. Consequently, the study on multipass AWJ cutting will be focused on the alumina ceramic only and use the jet impact angle of 80^o.

4. MULTIPASS CUTTING OPERATIONS

It is apparent that by properly controlling the AWJ cutting process, some cutting performance such as the depth of cut, can be improved without additional costs to the process. Nevertheless, there are situations where with a single pass AWJ cutting operation, the material thickness is beyond the jet's capacity to cut through, or the AWJ cannot produce smooth surface (no striations) over the thickness of the workpiece. An approach to increasing the depth of cut is to use multipass cutting where the jet travels over the same kerf for a number of times. Multipass cutting operations in conventional machining processes have been proven to be superior to single pass cutting from an economic and technological point of view [34]. This concept has been used in AWJ cutting in some investigations [20,29]. However, further studies are required to understand the quantitative benefits of using multipass AWJ cutting operations. In particular, there have been no reported studies to combine the multipass cutting technique with an appropriate jet forward impact angle to enhance the cutting performance, as well as to study the effect of jet traverse direction on the cutting performance. As mentioned earlier, if the first pass cannot cut through a polymer matrix composite, delamination may occur. Therefore multipass cutting is not suggested for increasing the total depth of cut when processing thick polymer matrix composites, but may be attempted to reduce kerf taper, increase surface finish and smooth depth of cut. Thus, the study of multipass cutting uses alumina ceramics only.

4.1 Multipass Cutting Experiments

The cutting tests were again conducted on a Flow International waterjet cutter which could produce the water pressure of up to 380 MPa (or 55,000 psi) and had a five-axis robot manipulator for positioning the cutting head (or nozzle). The diameter of the orifice used to form the waterjet was 0.33 mm, while the nozzle was 76.2 mm long and 1.02 mm in diameter. The abrasive material was 80 mesh almandine garnet sand and its mass flow rate was 8.33 g/s. Because of the re-configuration of the system, only this abrasive flow rate could be chosen for this experiment. For all the tests, a single level of standoff distance at 4 mm was used.

The study was carried out in two sets of experiments. In the first set, the jet impact angle was kept at 90^o while changing the other cutting parameters, cutting 12.7 mm thick 87% alumina ceramic tiles. Water pressure, jet traverse speed, and the number of passes were varied. In addition, the jet traverse direction was studied to examine its effect on the cutting performance; in some tests the jet traverse directions in all passes remained the same, while in others alternating directions were used for consecutive passes. Fig. 4 shows that terminologies used in the experimental work, while Table 1 shows the variables in the tests.

<take in Fig. 4>

<take in Table 1>

In the second set of tests, a jet impact angle of 80^o was used based on the foregoing study, as given in Table 2. 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. In these tests, 25.4 mm thick 87% alumina ceramic tiles were used at a single water pressure of 345 MPa or 50,000 psi. The jet traverse directions for all the passes in a multipass operation were kept the same.

<take in Table 2>

The selection of cutting parameters was made based on earlier studies in the authors' laboratory [4,8,27,29,32]. The cutting parameters were selected to ensure that the jet impact angle, water pressure and standoff distance were about their optimum value for single pass cutting of alumina ceramics, while the jet traverse speeds were selected in such a way that some were just able to cut through the material in one pass of cutting and some could not cut through in order to facilitate the study of multipass operations. Although the abrasive mass flow rate was unable to change, it would not affect the qualitative comparison of the cutting performance between single and multipass cutting. From this experimental design, a total of 144 passes of cutting have been conducted, producing 66 straight slots of 25 mm length. The cutting performance as measured by the total depth of cut, smooth depth of cut, kerf width, kerf taper and surface roughness was acquired with the assistance of metrological and optical instruments as described in the last section, and is analysed below.

4.2 Cutting Performance With 90^o Jet Impact Angle

Kerf profile

For the cutting conditions in this study, only the 1.0 mm/s jet traverse speed was able to cut through the 12.7 mm specimens in a single pass cutting. In such cases, the subsequent passes were found to be able to increase the smooth depth of cut, reduce the surface roughness and reduce the kerf taper angles. When the first pass was unable to cut through the material, a "pocket" was formed at the bottom of the kerf as shown in Fig. 5. Obviously, a multipass operation is indeed required to cut through the material. It can be seen from this figure that after the second and third cutting pass, the workpiece was cut through, but there is still a widened portion in the final kerf stemming from the pocket generated in the first pass. If this kind of kerf profile is not desirable, the cutting conditions in the first pass should be selected such that a through cut can be achieved, while the subsequent passes are used to increase the quality of the kerf.

The kerf taper steadily decreases as the number of passes increases, as shown in Fig. 6. In single pass cutting, the traverse speed has a considerable effect on the kerf taper, while this effect was reduced in multipass cutting. For instance, for the traverse speed range used in this study, the kerf taper angle has a large variation of about 2.5^o after the first pass cutting; however, after the second and third passes, its variation was reduced to only about 1^o. This trend can be noticed from Fig. 6(b). It can therefore be deduced that large traverse speeds may be used in multipass AWJ cutting for high cutting rate while not compromising the kerf taper. The experimental results showed that the number of passes did not have any significant effect on the top kerf width.

<take in Fig. 5>

<take in Fig. 6>

Total depth of cut and smooth depth of cut

The total depth of cut and smooth depth of cut are two major characteristics in AWJ cutting. While the total depth of cut represents the capacity of a jet to cut through a material, a large smooth depth of cut ideally equal to the total depth of cut required (or the material thickness) is often desirable. In this study, the smooth depth of cut was determined from the jet entry down to where clear striations on the cut surface were visible. It was apparent that the total depth of cut and smooth depth of cut increased with the number of passes. It is interesting and encouraging to note that with the same total cutting or elapsed time, a multipass cutting operation can produce larger total depth and smooth depth of cut than a single pass cutting. This is evidenced in Table 3. In general, with the same total cutting time, more passes at high traverse speed are favoured for increasing the smooth depth of cut. Alternatively, to achieve the same cutting performance, less cutting time is needed by using the multipass cutting mode.

It was also found that with the same jet traverse speed and other cutting conditions, the depth of cut produced in the second pass was generally less than that in the first pass. This trend is expected to apply to the third pass when comparing its depth of cut to that of the second pass. This is because of the increase in the actual standoff distance after the preceding pass. The increase in the standoff distance reduces the jet energy impinging on the material and hence, reduces the depth of cut.

<Take in Table 3>

<Take in Fig. 7>

Surface roughness

Surface roughness was measured at about 2 mm from the top edge of the kerfs using a Taylor-Hobson Surtronic 3+ stylus profilometer. The centre-line average measure R_a was used with a cut-off of 2.5 mm. Fig. 7 shows the effect of the number of passes and traverse speed on surface roughness. It can be noticed that surface roughness decreases constantly with an increase in the number of passes. This implies that there is a smoothening action on the kerf walls by the second and third pass that removes the ‘peaks’ left by the preceding passes. Furthermore, R_a increases as jet traverse speeds increases. This finding is similar to that for single pass cutting where high traverse speeds reduce the density of particles impinging the cutting front and the overlapping action of the jet, hence reducing the smoothening action.

It was interesting to note from the experimental results that the traverse speed for each pass in a multipass operation can be selected to achieve the same surface finish with less total cutting time. This is evidenced by the example in Fig. 7 where almost the same surface finish was achieved after the second and third pass with the traverse speeds of 1 mm/s and 2 mm/s. Furthermore, by increasing the number of passes while keeping the same elapsed time, a better surface finish can be achieved. For instance, after the second pass of cutting with a traverse speed of 2 mm/s, the R_a is smaller than that in a single pass cutting at 1 mm/s of jet traverse speed (Fig. 7).

4.3 Effect of Alternating Jet Traverse Direction

Examining the effect of jet traverse direction on the smooth depth of cut in double pass cutting reveals that in general, one directional cutting shows some advantage over the alternating directional cutting whereby a 4% to 20% increase in the smooth depth of cut has occurred by using the one directional cutting mode, as shown in Fig. 8(a). This is probably due to the fact that the particles in the second pass of alternating directional cutting will need to cut across the “peaks” produced on the kerf wall by the first pass so that their capacity to smoothen the surface in the lower region is reduced (note that there are drag angles on the particle traces). By contrast, one directional cutting allows the particles to impinge along the traces produced in the first pass so that the particles will not only cut the peaks left in the first pass, but also by-pass the “valleys” and smoothen the kerf wall in the lower region. Thus, one directional cutting should be used wherever possible such as in closed-loop profile cutting, but alternating directional cutting may be used in situations where nozzle empty return travel will otherwise be required. Since the first pass in all the multipass cutting operations with alternating jet traverse direction has cut through the material, the effect of nozzle traverse direction on the total depth of cut was unable to be compared, although it is believed that alternating the jet traverse direction will not have a significant effect on the total depth of cut.

<take in Fig. 8>

Alternating the jet traverse direction has not been found to have any significant effect on the kerf taper and top kerf width, but it eliminates the nozzle return travel in non-closed loop cutting situations.

It appears that alternating the jet traverse direction in multipass cutting has the tendency to increase the surface roughness. In the case where the traverse speed of 1 mm/s was used for all the three passes, the second pass worsened the surface roughness while the third pass reversed this negative effect, as shown in Fig. 8(b). In all the other cases, an increased surface roughness has been produced in the multipass cutting operations when alternating the jet traverse direction.

Consequently, as far as the surface finish is concerned, alternating jet traverse direction in multipass cutting is less favourable than the same directional cutting mode. Unlike in the same directional cutting where some particles will remove the peaks left in the previous passes and result in reduced surface roughness, the particles in cutting with alternating jet traverse direction will plough across the peaks produced by the previous pass so that a new pattern of surface profile is generated. This new pattern may or may not improve the surface roughness. It is thus recommended that the cutting mode of alternating jet traverse direction may be used where surface finish is not a major concern in order to eliminate the nozzle return travel.

4.4 Combined Effect of Jet Impact Angle and Multipass Cutting

By comparing the various cutting performance measures at 80^o and 90^o jet impact angles, it was found that, similar to single pass cutting, the jet impact angle did not result in significant change in the top kerf width. In some cases, the 80^o impact angle yielded a very slight increase (within 0.05 mm) in the top kerf width. Thus, top kerf width may be considered as being independent of jet impact angle. A similar tend was noticed of the effect of the impact angle on the kerf taper. It follows because jet structure or energy distribution and the destruction energy for the work material determine the kerf width, while jet impact angle has little effect on kerf width and kerf taper.

The effect of jet impact angle on the depth of cut is shown in Table 4. 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 an 80^o jet impact angle clearly shows the advantage in increasing the total depth of cut and smooth depth of cut in the upper smooth zone. Combining with the multipass cutting mode, 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 a 90^o jet impact angle, while the increase in the smooth depth of cut ranges from about 10% to 25%. When comparing to single pass cutting with the same total cutting time, the use of an 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. 9(a) shows how the combination of multipass cutting and using an 80^o jet impact angle can be employed in situations where a large smooth depth of cut is required.

<Take in Table 4>

<Take in Fig. 9>

As this work was not intended to study the surface roughness variation along the kerf wall from the jet entry to exit, the surface roughness values were obtained at about 2 mm from the top kerf edge for analysis. An examination of the experimental results has revealed that an 80^o jet impact angle did not have a noticeable effect on the surface roughness compared to that produced at a 90^o jet impact angle. This finding is consistent with that from the study on single pass cutting as mentioned earlier and shown in Fig. 3(b). From this figure, it can be seen that while the traverse speed affects the surface roughness for single pass cutting, the difference between the centre-line average R_a values at different traverse speeds diminishes and becomes indiscernible after the second and third pass in a multipass operation. Thus, high traverse speed can be used in multipass cutting with economic benefits and without compromising the surface finish.

5. CONCLUSIONS

As an increasingly used manufacturing technology, the capacity of AWJ cutting has limited its application domain. The study on the effects of jet impact angle on the major cutting performance measures has shown that a considerable gain of the depth of cut can be achieved by setting the jet impact angle at about 80^o in a single pass cutting of alumina ceramics. However, the benefit of using an 80^o jet impact angle showed only marginal improvement on some cutting performance measures such as the depth of cut when cutting a polymer matrix composite, as compared to cutting with a 90^o jet impact angle. The delamination defect associated with the non-through cuts of polymer matrix composite suggests that the cutting parameters should be selected to cut through the material in a single-pass cutting.

The study on multipass AWJ cutting has demonstrated that this cutting mode not only reduces the kerf taper, but also increases significantly the other major cutting performance measures such as the total depth of cut, smooth depth of cut and surface finish with the same total cutting time (or elapsed time) as in a single pass operation. Alternatively, to achieve the same cutting performance, multipass cutting operations can be used to reduce the cutting times and costs. Alternating the jet traverse direction in multipass cutting operations did not show major effect on the other cutting performance measures, but increased the surface roughness. It is thus recommended that the cutting mode of alternating the jet traverse direction may be used where surface roughness is not a major concern in non-closed loop cutting situations in order to eliminate nozzle empty return time. By contrast, the use of the same jet traverse direction for all the passes in a multipass operation should always be used in closed-loop contouring. Furthermore, this study has shown the benefits of using the multipass cutting mode together with an 80^o jet impact angle in cutting alumina ceramics. Thus, the multipass cutting technique can increase the cutting capacity and application domain of AWJ for situations where thick materials are processed.

The investigations on angling the jet and multipass cutting are limited to straight slit cutting. While these cutting techniques are expected to produce benefits in improving some of the cutting performance measures in contouring or curved slit cutting, theoretically, angling the jet results in geometrical errors on the machined profile in non-straight slit cutting. To quantify this error needs to take into account the jet tail-back effect when it cuts into the material. Further work is required to study the benefit of combining the multipass cutting and controlled nozzle oscillation techniques, as well as to develop predictive models for the cutting performance in multipass AWJ cutting.

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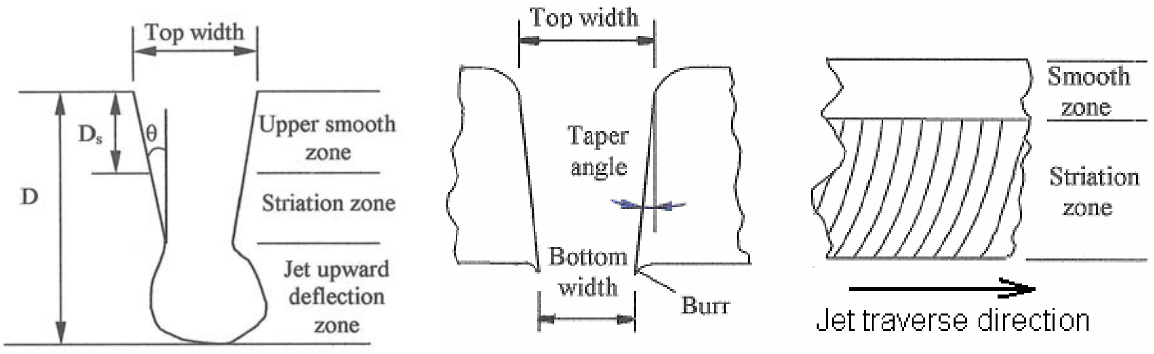

(a) Non-through cut (b) Through cut (c) Surface properties

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

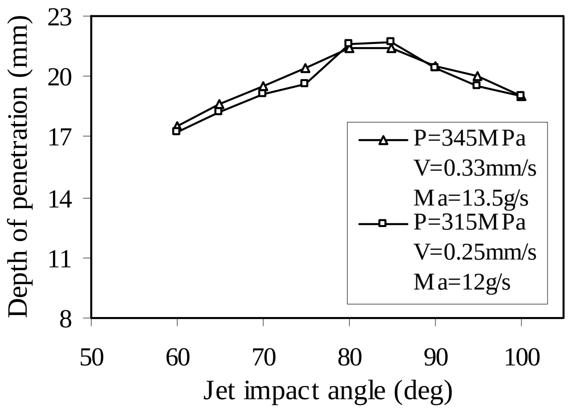

Fig. 2 Effect of jet impact angle on the depth of penetration when cutting ceramics (standoff = 4 mm).

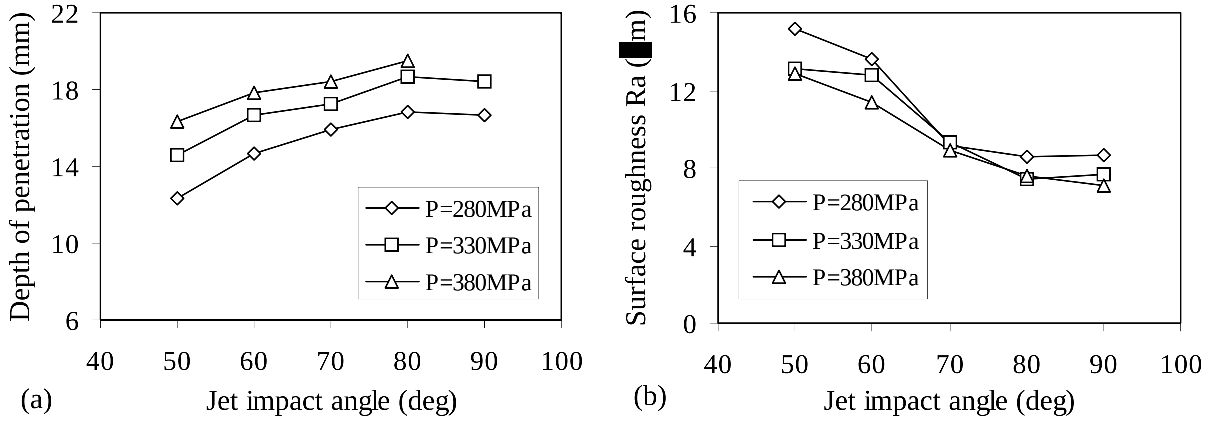

Fig. 3. Effect of jet impact angle on kerf characteristics when cutting polymer matrix composites (M_a=10 g/s, V = 26.67mm/s).

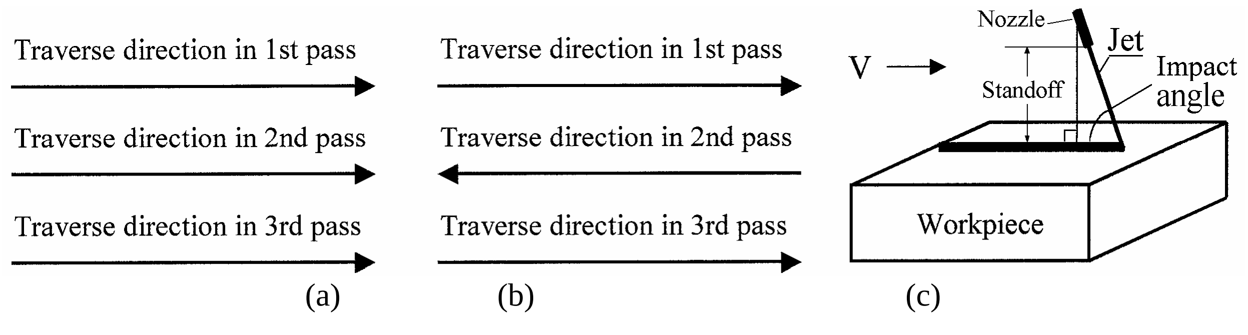

Fig. 4. Definitions of cutting parameters: (a) the same jet traverse direction for all passes, (b) alternating jet traverse direction, and (c) jet impact angle.

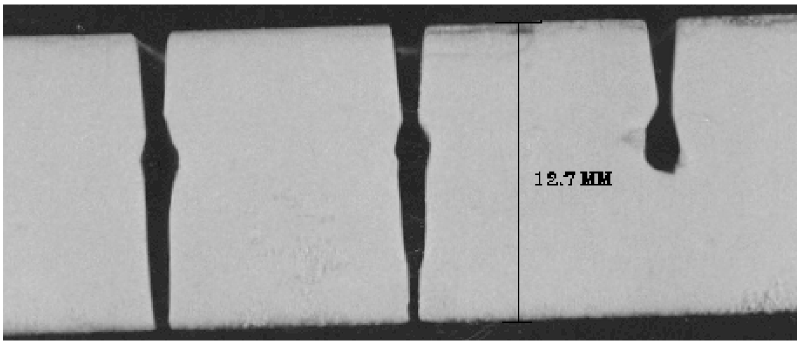

Fig. 5. Kerf profile in multipass AWJ cutting of ceramics (from right to left: single, double and triple pass at V=3.33 mm/s, P = 345 MPa).

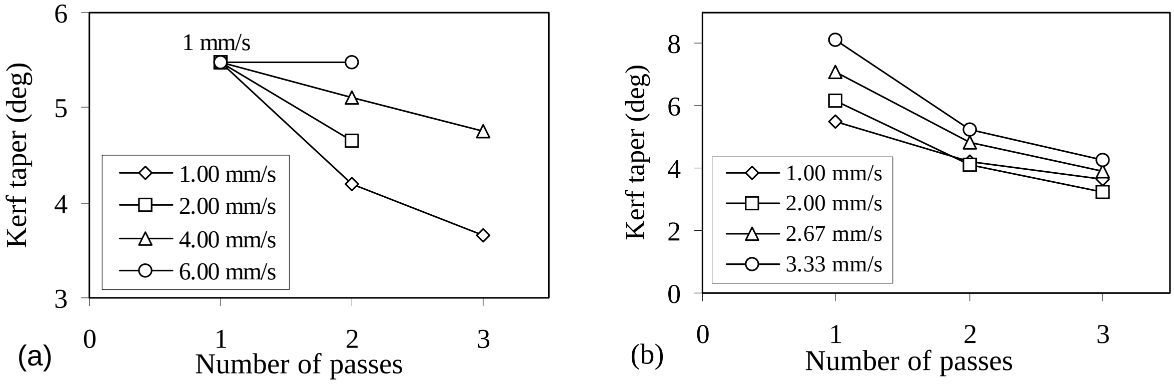

Fig. 6. Effect of process parameters on kerf taper in multipass cutting.

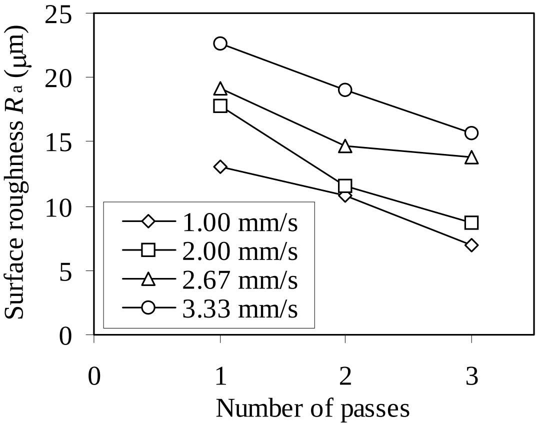

Fig. 7. Effect of process parameters on surface roughness in multipass cutting.

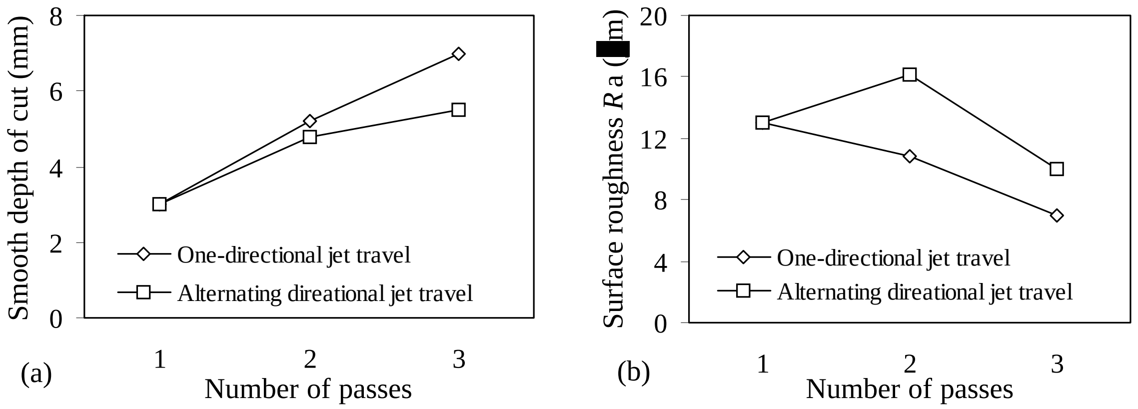

Fig. 8. Effect of jet traverse direction on the cutting performance in multipass operations at the water pressure of 345 MPa. (a) V_1=1 mm/s and V_2=V_3=4 mm/s; .(b) V_1=V_2=V_3=1 mm/s.

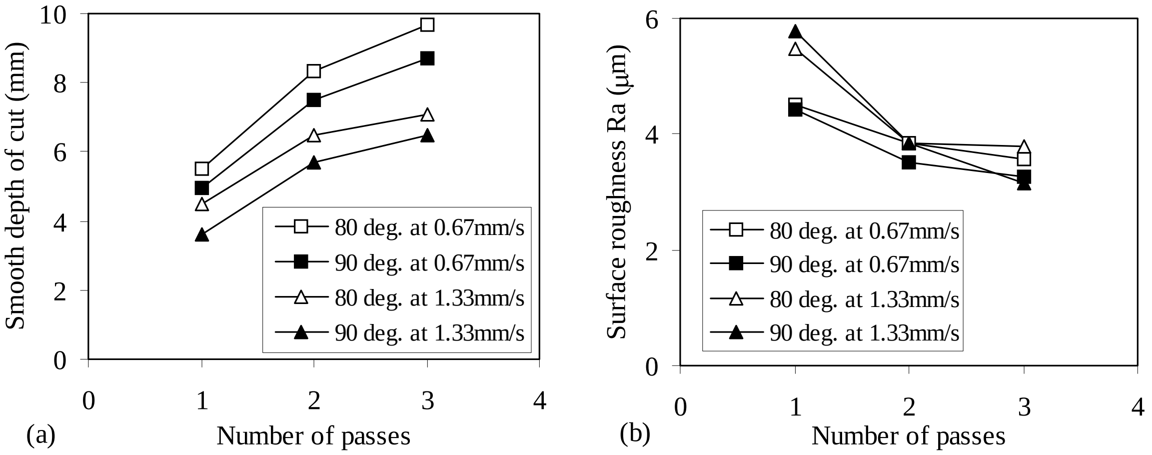

Fig. 9. Effect of jet impact angle in multipass cutting at different traverse speeds.

Table 1. Combinations of traverse speeds in the tests (*P* = 345 MPa and 380 MPa, jet impact angle = 90^o).

Jet traverse Speed (mm/s)	Combinations of jet traverse speeds												
	Same jet traverse direction							Alternating jet traverse direction					
	1	2	3	4	5	6	7	8	9	10	11	12	13
V_1	1	1	1	1	1	1	1	1	1	1	2	1	1
V_2		1	1	2	4	4	6	1	1	2	4	4	6
V_3			1		4				1		4		

	Same jet traverse direction (using the same *V* in all passes)								
	14	15	16	17	18	19	20	21	22
V_1	2	2	2	2.67	2.67	2.67	3.33	3.33	3.33
V_2		2	2		2.67	2.67		3.33	3.33
V_3			2			2.67			3.33

Table 2. Combinations of traverse speeds in the tests with different jet impact angles (P = 345 MPa, jet impact angle = 80^o and 90^o).

Jet traverse speed (mm/s)	Combinations of jet traverse speeds										
	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. Superiority of multipass cutting operations (jet impact angle=90^o, P=345Mpa, using the same jet traverse direction for all passes).

	Traverse speed in each pass					
Sample No.	V_1 (mm/s)	V_2 (mm/s)	V_3 (mm/s)	Elapsed time* (s)	Total depth (mm)	Smooth depth (mm)
1	1			25	>12.7	3
2	2	2		25	>12.7	5.2
3	1	2		37.5	>12.7	6.8
4	1	4	4	37.5	>12.7	7
5	2	2	2	37.5	>12.7	12
6	0.67			37.5	17.42	4.96
7	1.33	1.33		37.5	20.23	5.68
8	1.33	2.67	2.67	37.5	24.42	5.68

* Based on 25 mm length of cut and not including nozzle return time.

Table 4. Total depth and smooth depth of cut with different jet impact angles (jet travels in the same direction for all passes).

	Jet traverse speed			90^o jet impact angle		80^o jet impact angle	
Sample No.	V_1 (mm/s)	V_2 (mm/s)	V_3 (mm/s)	Total depth (mm)	Smooth depth (mm)	Total depth (mm)	Smooth depth (mm)
1	0.67			17.42	4.96	19.33	5.53
2	0.67	0.67		>25.4	7.50	>25.4	8.33
3	0.67	0.67	0.67	>25.4	8.72	>25.4	9.66
4	0.67	1.33		>25.4	6.78	>25.4	7.43
5	0.67	1.33	1.33	>25.4	7.62	>25.4	8.31
6	0.67	2.67	2.67	>25.4	6.64	>25.4	7.56
7	1.33			11.73	3.63	13.09	4.47
8	1.33	1.33		20.23	5.68	>25.4	6.50
9	1.33	1.33	1.33	>25.4	6.50	>25.4	7.10
10	1.33	2.67		18.92	5.01	23.04	5.68
11	1.33	2.67	2.67	24.42	5.68	>25.4	6.43