The cutting performance in multipass abrasive waterjet machining of industrial ceramics

Author/Contributor:
Wang, Jun; Guo, D.M.

Publication details:
Journal of Materials Processing Technology
v. 133
Chapter No. 3
pp. 371-377

Publication Date:
2003

Journal of Materials Processing Technology,
Vol. 133/3 (2003), pp 371-377.

The cutting performance in multipass abrasive waterjet machining of industrial ceramics

J. Wang* and D.M. Guo**
School of Mechanical, Manufacturing and Medical Engineering, Queensland University of Technology, GPO Box 2434, Brisbane, Qld. 4001, Australia

Abstract
An analysis of the cutting performance of multipass abrasive waterjet machining is presented based on an experimental investigation on an 87% alumina ceramic. It is shown that with a good combination of cutting parameters such as nozzle traverse speed, multipass cutting demonstrates distinct superiority over the single pass cutting. Plausible trends of kerf quality and depth of cut with respect to the number of passes, nozzle traverse speed and nozzle traverse direction are analyzed. A general guide for the selection of cutting parameters in multipass cutting are finally presented based on the analysis.

Keywords: Abrasive waterjet cutting; Cutting performance; Multipass waterjet cutting

1. Introduction

Abrasive waterjet (AWJ) cutting has been claimed to have 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 is being increasingly used in the manufacturing industries. It has been particularly gaining favour in cutting 'difficult-to-cut' materials such as ceramics and marbles [2-4], and layered composites [5-7] as well as in pattern or profile cutting on various materials.

Since the introduction of AWJ cutting technology, a large amount of effort has been directed to exploring its applications and the associated science [8]. This includes the study of the dynamic characteristics of the jet [9,10], the analysis of the machined surfaces and kerf geometrical features to optimize the cutting process [6,11-13], and the studies and predictive models for improving the cutting performance, such as the kerf quality (kerf taper, surface roughness and striation etc.), material removal rate and depth of cut or jet penetration, by using such techniques as angling the jet forward [2,6,7], nozzle oscillation [2], and increasing machine capability [14]. Nevertheless, there are situations where the material thickness is beyond the jet's capacity to penetrate in a single pass cutting. Furthermore, studies have shown that by reducing the jet exposure time (i.e. by increasing the jet traverse rate), the damping and friction effects on the jet can be reduced [15]. As a result, to achieve the same total depth of cut, multipass cutting at high traverse rates may offer advantages over a single pass cutting at low traverse rate. It is thus necessary to investigate the multipass AWJ machining process. Unfortunately, it appears that research on multipass AWJ cutting has received little attention [9,16,17].

---

* Fax: +61-7-3864 1469; Email: j.wang@qut.edu.au
** School of Mechanical Engineering, Dalian University of Technology, China.

In this paper, the cutting process and cutting performance for multipass AWJ machining will be presented based on an experimental investigation on an 87% alumina ceramic. The technological cutting performance as represented by kerf profile and geometry, cut surface quality and depth of cut (or depth of jet penetration) will be analyzed with respect to the cutting variables, i.e. the number of passes, the nozzle traverse speed and jet traverse direction (i.e. whether the jet travels in the same direction for all passes or in alternating direction in consecutive passes). An economic analysis of the multipass cutting process in terms of the cutting times is finally given together with a general guide and suggestion for the selection of the number of passes and the cutting parameters in each pass for a multipass AWJ cutting operation.

2. Experiments

The experiment was conducted on a Flow Systems International waterjet cutter which was equipped with a model 20X dual intensifier high pressure output pump (up to 380 MPa) and a five axis robot positioning system. The specimens were 87% alumina ceramic slabs of 12.7 mm thick whose properties are given in Table 1.

Although AWJ cutting involves a large number of variables and virtually all these variables affect the cutting results, only some major variables in multipass operations were considered in this work as others have been considered in previous studies on single pass cutting [2-4]. The selection of the test conditions (or experimental design) was to ensure that the feasibility of multipass operations and the effect of the number of passes on the major cutting performance measures could be assessed. In addition, the parameters that could be practically and easily changed in a multipass operation were considered. Thus, the jet traverse speed and jet traverse direction in each pass of a multipass operation were included in the experimental design. In some cases, the same jet traverse speed for all the passes were selected, while in other cases, different traverse speeds were used for each pass. The combinations of the values for jet traverse speeds were selected in such a way that the cutting performance within the same total cutting time could be compared to assess the superiority of multipass over single pass cutting and to study the trends on which the benefit of using multipass operations can be maximized. Furthermore, in practice, it is possible to use either the same jet traverse direction for all the passes (such as in closed-loop contouring) or alternate the jet traverse direction for any consecutive passes (such as in straight slotting with no nozzle empty return travel). Therefore, the experimental design also enabled to study the effect of jet traverse direction on the cutting performance.

Table 2 gives the number of passes and the combinations of the traverse speeds. In the first and second sets of the tests, the first pass was able to cut through the specimens, while in the third set more than one passes were needed to penetrate the material. The water pressures used were 345 MPa (50,000 psi) and 380 MPa (55,000 psi) and the abrasive used was 80 mesh almandine garnet sand. The other parameters were kept constant, they were 90°of jet impact angle, 8.33 g/s (or 0.5 kg/min) of abrasive mass flow rate, 4 mm of stand-off distance between the nozzle and the workpiece, 0.39 mm of orifice diameter, 1.02 mm of nozzle diameter, and 76.2 mm of nozzle length. Thus a total of 94 passes of cutting have been conducted which produced 44 slots of 25 mm long. The relevant data for the cutting performance measures (kerf profile, kerf taper, depth of cut, surface roughness etc.) have been acquired from each cut for analysis.

3. Analysis of cutting performance

For single pass cutting, it has become clear from the literature [2,4,6,7] that three cutting zones exist in the processing of materials under an AWJ, i.e. the cutting zone at shallow angles of attack, the cutting zone at large angles of attack, and the jet upward deflection zone. The attack angle is defined as the angle between the jet flow direction and the target surface at the point of attack. Hashish [12] 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 [2]. It has also been found by researchers that the surfaces produced by an AWJ consists of an upper smooth zone which is free of striations and a lower rough zone where the surface is characterized by wavy striations, as shown in Fig. 1. In the jet upward deflection zone (for non-through cuts only), a large pocket is formed. The geometry of the kerf generated by an AWJ is characterized by a wider entry at the top and a narrow exit at the bottom so that a taper is produced. The characteristics of kerfs produced in multipass cutting will be analyzed below with the same jet traverse direction for all passes first, followed by examining the effect of jet traverse direction.

3.1 Kerf profile

A visualization study has found that in general the kerfs produced by a single pass cutting resemble the characteristics reported in previous investigations. When the first pass was able to penetrate the work materials, such as those in tests numbers 1 to 13 for both water pressures, the kerf is characterized by a wide top and narrow bottom. It appears that since the jet in one pass cutting was just able to penetrate the specimen, the low portion of the kerf was widened due to the deformation wear effect in this region and the cracking of the material in the exit edges. In the case where a through cut was produced by the first pass, the second and third pass have been found to be able to reduce the kerf taper (kerf wall inclination) so that the two side walls tend to be parallel to each other.

When the first pass was unable to penetrate the workpiece, the kerfs again show similar characteristics to those reported earlier, as shown in Fig. 2 (right), i.e. the kerf has a wider opening but reduces gradually with a large pocket at the bottom due to the jet upward deflection. In such a case, multipass is indeed necessary to cut through the material. The economic and technological viability of multipass compared to single pass cutting will be discussed later in the paper. It can be seen from Fig. 2 that while the second and third passes were able to cut through the workpiece and reduce the kerf wall inclination in the upper and lower portions, there is still a widened portion in the final kerf stemming from the large pocket generated in the first pass. The cutting speeds and the number of passes did not result in significant variations in the top kerf width.

3.2 Kerf taper

The kerf wall inclination or kerf taper angle for each cut was determined from the equation:

$$\theta = \tan^{-1}\left(\frac{W_{top} - W_{bottom}}{h}\right) \quad (1)$$

where W_{top} and W_{bottom} are the top and bottom kerf width respectively, h is the distance from the top kerf to where the W_{bottom} is measured. For cases where the first pass could not cut through the workpiece, the W_{bottom} was measured at just above the large pocket. Based on this equation, the kerf taper angle may be considered as the average of the angles on the two kerf walls.

An analysis has found that the kerf taper angle decreases considerably and consistently with an increase in the number of passes, as shown in Figs. 3 (a) and (b), although this decrease is only marginal when the traverse speed in the second pass is at 6 mm/s (or 360 mm/min), in which case neither the number of particles impinging the material, nor the particle energy, are sufficient to widen the kerf generated by the first pass at 1 mm/s (or 60 mm/min) of jet traverse spped. The experimental data also show that when the first pass is at 1 mm/s, the kerf taper angle is affected by the traverse speed in the subsequent passes. Lower speed is always favourable in achieving smaller kerf taper angle, although the taper angle difference for different traverse speeds is only within 1.5° after the second and third pass of cutting. When the same traverse speed is applied to all the passes as for set 3 of the tests in Table 2, the kerf taper angles after the first pass exhibit a relatively large variation of about 2.5° for different speeds. After the second and third pass, the taper angles were reduced, and its variations for different traverse speeds were only about 1°. These trends are shown in Fig. 3(b), from which it can be deduced that a large traverse speed at around 3.33 mm/s (or 200 mm/min) may be used for high cutting rate and low cost while not significantly sacrificing the kerf taper.

3.3 Depth of cut and smooth depth of cut

The depth of cut and smooth depth of cut are two major characteristics in AWJ cutting. While the depth of cut represents the capacity of jet to penetrate into the material, a large smooth depth of cut ideally equal to the total depth of cut required is always desirable. In this study, the smooth depth of cut was determined from the jet entry kerf down to where clear striations on the cut surface are visible. When examining the depth of cut for single pass cutting, only the 1 mm/s traverse speed was able to cut through the workpiece. It is found that the depth of cut steadily decreases as the traverse speed increases as would be expected, so does the smooth depth of cut. It was found that the total depth of cut and smooth depth of cut increase with the number of passes. For the work material and traverse speeds used in this study, a through cut could always be achieved in no more than two passes. The third pass was in fact to improve the kerf quality. Fig. 4 shows the effect of the number of passes on the smooth depth of cut.

With the same total cutting or elapsed time, it appears that a two pass cutting at 2 mm/s show potential to penetrate deeper into the materials than a single pass cutting at 1 mm/s. It is apparent that a single pass at 1 mm/s was just able to cut through the specimens while a double pass cutting at a speed as high as 3.33 mm/s did not show any difficulty in penetrating the material, with considerable time (and cost) savings. Irrespective of the pocket produced by the first pass on non-through cuts, a multipass cutting with less elapsed time appears to be able to produce more smooth depth of cut and better surface finish than a single pass cutting in all cases. For the purpose of comparison, Table 3 summarizes some of the data at 345 MPa water pressure when the jet travels in the same direction for all the passes. It can be seen that a proper selection of the number of passes and the traverse speed in each pass can increase the smooth depth of cut. In general, with the same total cutting time, more passes at high traverse speed are favoured for increasing the smooth depth of cut (and surface finish). Alternatively, to achieve the same cutting performance, less cutting time may be achieved by using multipass cutting.

For all the test conditions, only the single pass cutting at 2 mm/s, 2.67 mm/s and 3.33 mm/s could not cut through the material so that a quantitative analysis of the total depth of cut could not be undertaken. For this reason, some additional tests on 25.4 mm thick specimens were conducted with the jet traveling at the same direction for all the passes. Table 4 shows the superiority of multiupass over single pass cutting for some major cutting performance measures from these additional tests, which confirms the above analysis.

3.4 Surface finish

The surface roughness was measured at about 2 mm from the top edge of the kerfs using a Taylor-Hobson Surtronic 3+ stylus profilometer. The central-line average measure R_a was used with a cut-off of 2.5 mm. Some typical results are given in Table 3, while Fig. 5 highlights the effect of the number of passes and traverse speed on surface roughness. It can be noticed that the surface roughness decreases constantly with an increase in the number of passes. This implies the smoothening action on the kerf walls by the second and third passes to remove the 'peaks' left by the precedent pass. Furthermore, R_a increases as the cutting speed increases. This finding is similar to that of single pass cutting [4] where high speed reduces the density of particles impinging the cutting front and, hence, reduces the smoothening action.

It is interesting to note that the traverse speed in each pass can be selected to achieve the same surface finish with less total cutting time. This is evident from Fig. 5 where almost the same surface finish is achieved after the second and third pass with 1 and 2 mm/s traverse speeds. Table 3 also displays this trend. Furthermore, by increasing the number of passes while keeping the same or less elapsed time, better surface finish may be achieved (e.g. test numbers 1 and 15, and 4 and 16 in Table 3).

3.5 ***Effect of jet traverse direction***

Examining the effect of jet traverse direction on the smooth depth of cut in double pass cutting reveals that in general, multipass cutting with one directional jet travel shows some advantage over the alternating directional jet travel whereby a 4% to 20% increase in the smooth depth of cut has occurred by using the one directional jet travel mode. This advantage was further increased when three passes of cutting was used, as shown in Fig. 6(a). This is probably due to the fact that the particles in the second pass of alternating directional travel mode will need to cut across the "peaks" produced on the kerf wall in the first pass so that their capacity to smoothen the surface in the lower region is reduced (note that there is a drag angle on the particle traces). By contrast, cutting with one directional jet travel allows the particles to impinge along the traces produced in the first pass so that some particles will by-pass through the "valleys" and smoothen the kerf wall in the lower region. Thus, one directional jet travel mode should be used wherever possible such as in closed-loop profile cutting, but alternating directional cutting may be an alternative 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.

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 worsen 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. 6(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 jet travel mode where some particles will remove the peaks left in the previous passes and result in reduced surface roughness, the particles in the alternating jet travel directional cutting will plough across the peaks produced by the previous pass so that a new pattern of peaks is generated. This new pattern of surface profile may or may not improve the surface roughness. It is thus recommended that the cutting mode of alternating jet travel direction may be used where the surface finish is not a major concern to eliminate the nozzle return travel.

4. Economic and process design considerations

The foregoing analysis has shown that with the same cutting (or total cutting) time, multipass cutting at higher jet traverse speeds is able to produce kerfs of smaller taper angle and better surface finish and to yield larger depth of cut and smooth depth of cut than a single pass cutting at a lower jet traverse speed. Consequently, if the kerf quality and the depth of cut are pre-determined for a given job, the use of multipass AWJ cutting will reduce the total actual cutting time required for the job, hence increasing the productivity. This also indicates the reduction of production costs including the abrasive consummation that is proportional to the actual cutting time. Further economic and technological benefits can be achieved by determining the appropriate number of passes and properly selecting the jet traverse speed in each pass of a multipass operation. For the material under consideration and with the first pass at 1 mm/s, using a 2 mm/s jet traverse speed in the second pass produced comparable kerf quality (R_a and smooth depth) to that by 1 mm/s, while 4 mm/s made the R_a worse than that produced by the first pass, as shown in Table 3. Thus, if two passes are used and a through cut is preferred in the first pass, the traverse speed of 2 mm/s in the second pass may be used from the above analysis. Because it is not practical to alter the abrasive mass flow rate and water pressure for each pass in a multipass operation, no attempt has been made in this regard for economic and technological gains.

The selection of the jet traverse speed for the first pass has an important impact to the kerf profile and geometry. If the first pass cannot penetrate the material, a pocket will be produced and remain on the kerf wall. If this is not desired, the process parameters for the first pass should be selected such that a through cut is achieved where possible, while the subsequent passes are used to improve the kerf quality. Some depth of cut models [2,3,8,9] can be used for this purpose. For the material used in this study, a double pass cutting with the cutting speeds of 1 mm/s and 2 mm/s may be used for the first and the second pass, respectively. If the pocket in the middle of the kerf wall is not a major concern such as in most pattern cutting where only the top kerf is eventually visible, a good combination of traverse speeds in different passes will result in economic superiority as indicated in the present study, e.g. an equal double pass cutting at 2.67 mm/s or 3.33 mm/s can yield considerable time and cost savings while producing better surface finish and larger smooth depth of cut than a single pass cutting at 1 mm/s. In cases where a single pass is unable to penetrate a thick workpiece, multipass cutting will become essential to cut through the material and to improve the kerf quality. An optimization procedure is yet to be developed to optimize the number of passes and the cutting parameters in each pass once realistic mathematical models for all the cutting performance measures become available.

From this study, alternating the nozzle traverse direction in each pass has a negative effect on the surface finish and provides less improvements on the smooth depth of cut than the one directional cutting mode, although the kerf taper and total depth of cut were not significantly affected by changing the jet travel direction. Nevertheless, unless in the situation of closed-loop profile cutting where the nozzle can travel more than one loops (multiple passes in the same nozzle traverse direction) to take the full advantages of multipass cutting, alternating directional cutting can still be considered to cut thick materials and to improve the smooth depth of cut and kerf taper. This is because of the considerable time loss associated with one directional cutting in non-loop cutting situations where the nozzle needs empty return travel and the pump normally needs to be shut down for this procedure.

5. Conclusions

An analysis of the technological and economic performance of multipass AWJ machining has been presented based on an experimental investigation. It has been shown that with the same cutting time, the use of multipass cutting can improve the technological performance as compared to a single pass cutting. Alternatively, if the requirement for a job is known, multipass AWJ cutting can be used to reduce the total actual cutting time and cost. Plausible trends of the kerf quality and depth of cut with respect to the number of passes, nozzle traverse speed and nozzle traverse direction have been analyzed. This analysis has highlighted the superiority of using multipass over single pass AWJ cutting, and provided a guideline for the selection of cutting parameters.

Acknowledgements
The authors wish to thank Mr. Y.M Wong for his assistance in the experimental data acquisition.

References

1. C.A. van Luttervelt, On the selection of manufacturing methods illustrated by an overview of separation techniques for sheet materials, *Annals of CIRP*, 1989, 38(2): 587-607.
2. E. Siores, W.C.K. Wong, L. Chen and J.G. Wager, Enhancing abrasive waterjet cutting of ceramics by head oscillation techniques, *Annals of CIRP*, 1966, 45(1): 215-218.
3. J. Zeng and T.J. Kim, Material removal of polycristalline ceramics by a high pressure abrasive water jet - an SEM study. *Int. J. Water Jet Technol.*, (1)1991: 65-71.
4. G.V.S. Prasad, J. Wang and W.C.K. Wong, Kerf formation analysis in the abrasive waterjet machining of industrial Ceramics, *Advances in Abrasive Technology* II - 2nd Int. Symp. on Advances in Abrasive Technology (ISAAT'98), Shanghai, 1998, pp. 213-220.
5. D. Arola and M. Ramulu, A study of kerf characteristics in abrasive waterjet machining of graphite/epoxy composite, *J. Eng. Materials and Technol.*, (118)1996: 256-265.

6. J. Wang, Abrasive waterjet machining of polymer matrix composites: Cutting performance, erosive analysis and predictive models, *Int. J. Adv. Manuf. Technol.*, 15(1999): 757-768.
7. J. Wang, A Machinability Study of polymer matrix composites using abrasive waterjet cutting technology, *J. Mater. Proc. Technol.*, 94/1(1999): 30-35.
8. A.W. Momber and R. Kovacevic, *Principles of Abrasive Water Jet Machining*, Springer-Verlag, London, 1998.
9. M. Hashish and M.P. Du Plessis, Prediction equations relating high velocity jet cutting performance to standoff distance and multipasses, *J. Eng. Ind.*, 101(1979): 311-318.
10. E. Siores, L. Chen et al, Improving surface finish generated by the abrasive waterjet process, in: Zhang, L & Yasunaga, N (eds), *Advances in Abrasive Technology*, World Scientific, 1997: 187-191.
11. A.W. Momber, L. Eusch and R. Kovacevic, Machining refractory ceramics with abrasive waterjet. *J Mater. Sci*. 31(1996): 6485-6493.
12. M. Hashish, A modelling study of metal cutting with abrasive waterjets, *J. Eng. Mater. Technol.*, 106 (1984): 88-100.
13. M. Hashish, Characteristics of surfaces machined with abrasive waterjets, *J. Eng. Mater. Technol.*, 113(1991): 354-362.
14. M. Hashish, D.E. Steele and D.H. Bothell, Machining with super-pressure (690 MPa) Waterjets, *Int. J. Mach. Tools Manufact.*, 37(1997): 465-479.
15. A.W. Momber, R.S. Mohan and R. Kovacevic, On-line analysis of hydro-abrasive erosion of pre-cracked materials by acoustic emission. *Theoretical & Appl. Fracture Mech.*, 31(1999): 1-17.
16. A. Bortolussi and R. Ciccu, Contour cutting of thick steel plates. Proc. 14^{th} Int. Conf. Jetting Technol., Belgium, 1998: 15-24.
17. F. Hu, Y. Yang, E.S. Geskin, et al. Characterization of material removal in the course of abrasive waterjet machining. Proc. 6th Amer. Water Jet Conf, Houston, Taxas, 1991, pp 17-29.

Table 1. Physical and mechanical properties of the test specimens (87% alumina ceramics).

Hardness (Rockwell C)	79	Tensile strength (MPa)	221
Compressive strength (MPa)	2480	Modulus of elasticity (GPa)	276
Flexural Strength (MPa)	336	Average crystal size (μm)	1.6

Table 2. Combinations of traverse speeds used in the tests (V in mm/s).

Set 1: One directional				Set 2: Alternating directional				Set 3: One directional			
Test No.	V_1	V_2	V_3	Test No.	V_1	V_2	V_3	Test No.	V_1	V_2	V_3
1	1							14	2		
2	1	1		8	1	1		15	2	2	
3	1	1	1	9	1	1	1	16	2	2	2
4	1	2		10	1	2		17	2.67		
5	1	4	4	11	1	4	4	18	2.67	2.67	
6	1	4		12	1	4		19	2.67	2.67	2.67
7	1	6		13	1	6		20	3.33		
Water pressure: 345 and 380 MPa for the 22 combinations.								21	3.33	3.33	
								22	3.33	3.33	3.33

Table 3. Effect of the number of passes and traverse speed (water pressure = 345 MPa, one directional jet travel).

Test No.	1	2	3	4	5	6	7	15	16	18	19	21	22
V_1, mm/s	1	1	1	1	1	1	1	2	2	2.67	2.67	3.33	3.33
V_2, mm/s		1	1	2	4	4	6	2	2	2.67	2.67	3.33	3.33
V_3, mm/s			1		4				2		2.67		3.33
Total cutting time*, s	25.0	50.0	75.0	37.5	37.5	31.3	29.2	25.0	37.5	18.8	28.1	15.0	22.5
Smooth depth, mm	3.0	7.0	7.0	6.8	7.0	5.2	4.7	12.0	12.0	10.0	12.0	9.0	10.5
R_a, μm	13.0	10.9	7.0	11.4	13.7	16.0	20.4	11.6	8.7	14.7	13.8	19.0	15.7

* Based on 25mm long of cut and not including nozzle return travel.

Table 4. Superiority of multipass cutting operations (water pressure = 345 MPa, one directional jet travel).

Jet traverse speed in each pass			Elapsed time*	Total depth	Smooth depth
V_1 (mm/s)	V_2 (mm/s)	V_3 (mm/s)	(s)	(mm)	(mm)
0.67			37.5	17.42	4.96
1.33	1.33		37.5	20.23	5.68
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.

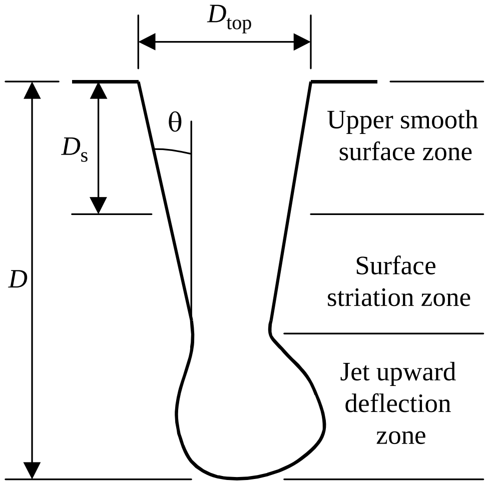

Fig. 1. Schematic of kerf profile for non-through cuts in single pass cutting.

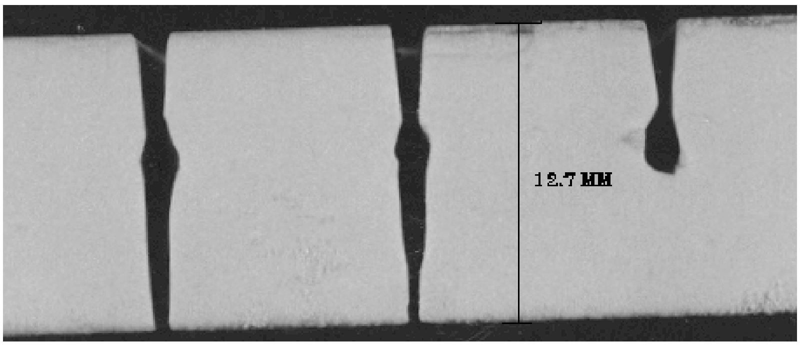

Fig. 2. Kerf profile in multipass AWJ cutting (from right to left: single, double and triple pass at V=3.33 mm/s, water pressure = 345 MPa, one-directional jet travel).

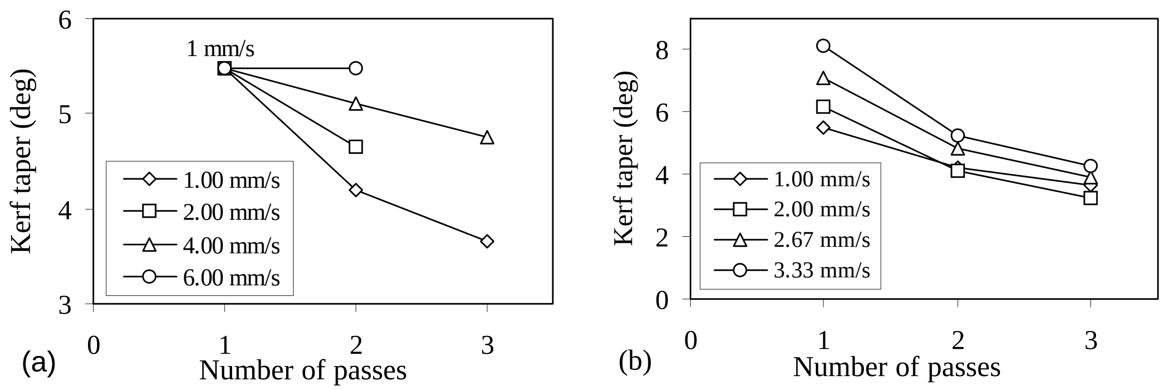

Fig. 3. Effect of process parameters on kerf taper (one-directional jet travel, water pressure=345 MPa).

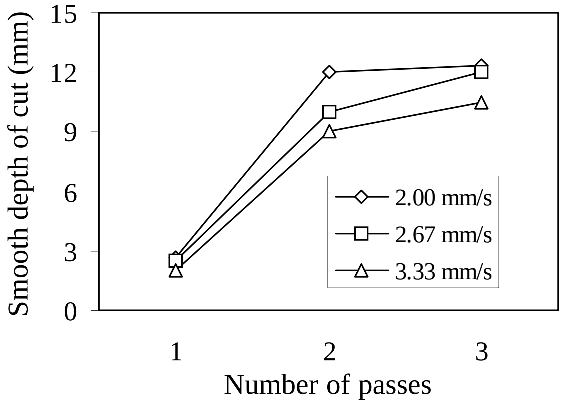

Fig. 4. Effect of number of passes on the smooth depth of cut at different jet traverse speeds (one-directional jet travel, water pressure=345 MPa)

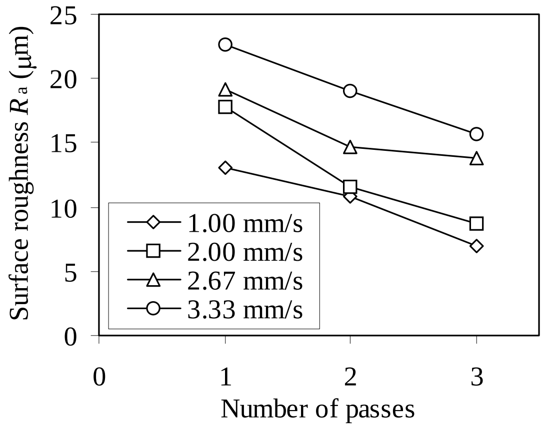

Fig. 5. Effect of process parameters on surface roughness (one-directional jet travel, water pressure=345 MPa).

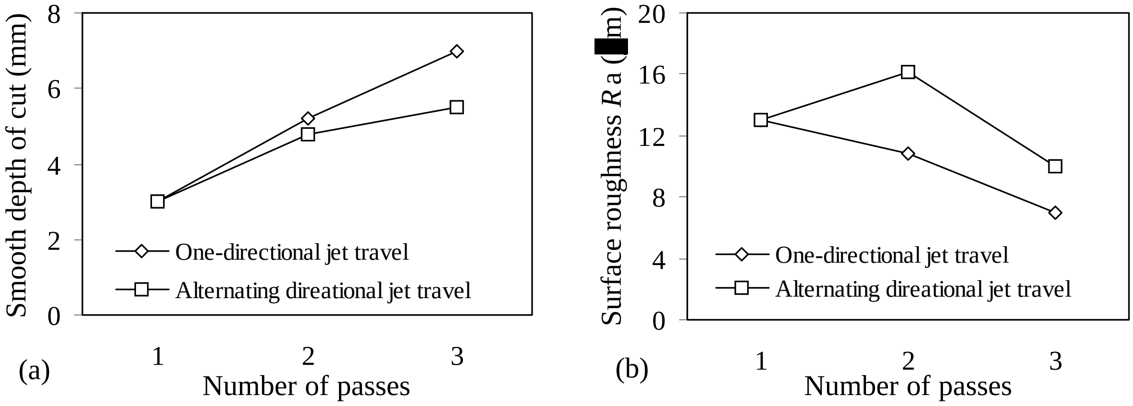

Fig. 6. Effect of jet traverse direction on the cutting performance in multipass operations at the water pressure of 345 MPa. (a) V_1=1 mm/s and V_2=V_3=4 mm/s; .(b) V_1=V_2=V_3=1 mm/s.