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Techniques for Enhancing the Cutting performance of Abrasive Waterjets

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Keywords: Abrasive Waterjet Cutting, Cutting Performance, Jet Impact Angle, Nozzle Oscillation, Multipass Cutting

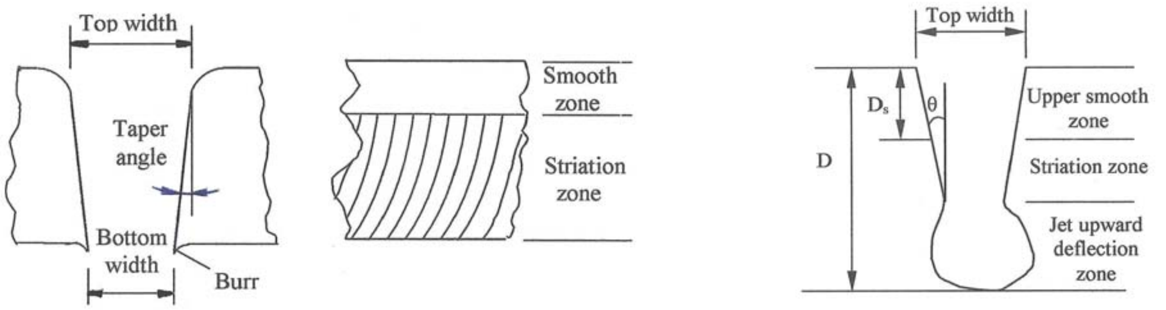
Abstract. The need to enhance the cutting performance and capability of abrasive waterjet (AWJ) technology has been a focal point in this field of research to increase its application domain. Various new cutting techniques for increasing the AWJ cutting performance, such as the total depth and smooth depth of cut, are outlined and discussed. It is found that considerable gains can be achieved by angling the jet forward in the cutting plane while multipass cutting technique is more effective in cutting thick materials. Using alumina ceramics as specimens, it shows that the use of nozzle oscillation can significantly improve the major cutting performance even with small oscillation angles, making it possible to use this technique in AWJ contouring. It also shows that if the oscillation parameters are not selected correctly, the nozzle oscillation technique can markedly reduce the cutting performance. A recommendation is then made on selecting the appropriate oscillation parameters for cutting alumina ceramics.

Introduction

As an increasingly used non-traditional machining technology, Abrasive Waterjet (AWJ) cutting is superior to many other cutting technologies in processing various materials, particularly in contouring or profile cutting and in processing difficult-to-cut materials [1-3]. However, its cutting capability in terms of depth of cut and kerf quality is the major obstruction limiting its application. A large amount of research and development effort has been directed towards modeling and improving AWJ cutting performance, such as surface roughness and striation as well as depth of cut (or depth of jet penetration) [3-7], and the fundamental understanding and mathematical modeling of AWJ hydrodynamic characteristics [3,8,9]. Nevertheless, AWJ cutting is still limited to situations where the work material is relatively thin and the requirement for cut quality is not high. Fig. 1 shows some typical kerf geometrical features for assessing kerf quality [3]. While the total depth of cut represents the jet capacity to cut through a material, in practice it often requires that a smooth surface is achieved over the entire work thickness, i.e. the smooth depth of cut is at least equal to the work thickness.

In order to increase the depth of cut 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. As a result, various attempts have been made to increase the cutting performance of AWJs, including the use of water pressure at as high as 690 MPa [10]. Among these investigations, angling the jet forward in the cutting plane, the controlled nozzle oscillation technique, and multipass cutting operations have been found to be most effective without any additional costs to the process.

Based on the research in the author's laboratory, this paper briefly reviews the jet forward angle and multipass cutting techniques. It then outlines a study of controlled nozzle oscillation technique along with an analysis of the associated cutting performance. The study focuses on the major cutting performance measures, such as depth of cut, smooth depth of cut and surface finish when cutting an alumina ceramic. Some remarks are finally made with regard to the limitations of these cutting techniques and the need for further research.



Through cut Non-through cut

Fig. 1. Characteristics of kerfs produced by an AWJ.

Forward Angling the Jet in the Cutting Plane

It can be noticed from Fig. 1 that as an AWJ cuts into a material, the direction of cutting changes as indicated by the drag angles on the cut surface. This change in particle cutting direction reduces the component of energy used for material removal. It has been thus suggested that a jet forward impact angle in the cutting plane could be introduced to compensate for the drag angle so as to improve cutting performance, where the jet impact angle is defined as the angle between the initial jet flow direction and the workpiece surface. To assess the effectiveness of this cutting technique and to optimize the cutting parameters, a study has been carried out on cutting 87% alumina ceramic tiles and polymer matrix composite slabs [3].

The results for cutting alumina ceramic tiles showed that jet impact angle had a significant effect on the depth of cut while its optimum value was found to be about 80^o to 85^o. It appears that this optimum value is independent of the other variables used in this study. Using the optimum jet impact angle could increase the depth of cut by about 30% compared to that at 60^o jet impact angle, or about 8% if compared to that when the jet is normal to the workpiece surface.

The depth of cut in cutting the composite slabs was found to increase by about 25% as the jet impact angle increased from 50^o to 80^o. A further increase in jet impact angle resulted in a decrease in the depth of cut. However, jet impact angle does not significantly affect the smooth depth of cut, but results in a marked improvement (up to 50% reduction) in the surface roughness when it is increased from 50° to 70°. This increasing trend vanishes as the jet angle is further increased to 90°. Thus 80° may be considered as the optimum jet impact angle for this material.

Multipass Cutting Operations

In practice, a material thickness may be beyond the jet's capacity to cut through in a single pass cutting, or the AWJ cannot produce a smooth surface over the workpiece thickness. An approach to increasing the depth of cut is to use multipass cutting where the jet travels over the same kerf a number of times. This concept has been studied in AWJ cutting of 87% alumina ceramics [3,11] and the major findings are presented.

The study shows that multipass cutting can significantly enhance the cutting performance of AWJs. Both the total depth of cut and smooth depth of cut increased with the number of passes. When the first pass was able to cut through the material, subsequent passes increased the smooth depth of cut, reduce the surface roughness and reduce the kerf taper angles. Thus, the use of multipass cutting has increased the application domain of this technology. It is interesting 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, i.e. with the same total cutting time, more passes at higher traverse speeds are favoured. This is evidenced in Table 1. This implies that to achieve the same cutting performance, less cutting time is needed by using a multipass cutting operation. Similarly, surface roughness decreased constantly with an increase in the number of passes, and by increasing the number of passes while keeping the same elapsed time, a better surface finish can be achieved.

A further study of combining the techniques of multipass cutting and forward jet impact angle has been carried out and demonstrated the resulting technological and economic advantages [12].

Table 1. Superiority of multipass over single pass cutting operations.

	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	3.00
2	2	2		25	>12.7	5.20
3	0.67			37.5	17.42	4.96
4	1.33	1.33		37.5	20.23	5.68
5	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.

Controlled Nozzle (or Cutting Head) Oscillation

It is well known that the surfaces generated by an AWJ consist of an upper smooth zone and a lower striation zone (Fig. 1). As jet traverse speed increases, surface roughness increases, so does the waviness or striation. It is believed that if a jet is used in such a way that it scans the surface of cut, the surface roughness and striation can be reduced. For this purpose, a controlled cutting head (or nozzle) oscillation technique was developed where a forward and backward pendulum-like oscillation of the nozzle along the cutting plane at pre-determined frequency and angular amplitude is superimposed to the jet traverse motion, as shown in Fig. 2. This technique has been found to be able to significantly improve the AWJ cutting performance.

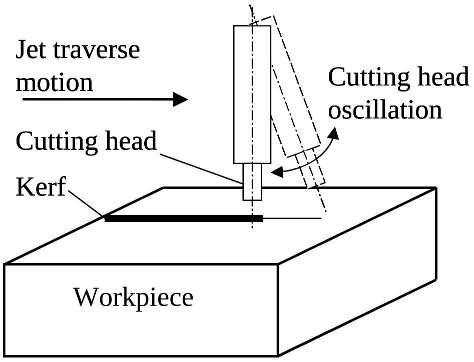


Fig. 2. Schematic of cutting head oscillation.

In a study on cutting 87% alumina ceramics [5], Siores et al. found that the average smooth depth of cut on the two kerf walls increases with the oscillation angle within the range of their test. In general, using nozzle oscillation can increase the smooth depth of cut by more than 30%. Even in the striation zone, the drag angle and waviness can also be significantly reduced. However, when the oscillation angle was increased to above 20^{o}, the smooth depth of cut on one of the kerf walls was increased significantly compared to the traditional cutting mode (no oscillation and 90^{o} jet impact angle), while the smooth depth on the other side was worse off significantly. This was claimed to be a result of an unbalanced and vibration in the cutting head at large oscillation angles. Consequently, the optimum oscillation angle was found to be 15^{o}-20^{o}. When analyzing the overall results, it was found that the optimum oscillation frequency, in value, is about 6 times the jet traverse speed, e.g. for a 0.5 mm/s traverse speed, the optimum oscillation frequency is about 3 Hz.

Similar studies were conducted on cutting mild steels and aluminium alloys [13] and fibre-reinforced composites [14], which show that up to 40% increase in the smooth depth of cut can be achieved by using nozzle oscillation.

However, it has been noticed in recent studies that if the oscillation parameters are not correctly selected, nozzle oscillation may have adverse effects on the cutting performance, such as reducing the smooth depth and surface roughness. The conditions at which nozzle oscillation increases or decreases the cutting performance need to be identified and the cutting and oscillation parameters are optimized. In addition, it should be realized that angular nozzle oscillation in the cutting plane results in theoretical geometrical errors in curved-slit cutting or contouring, while the reported studies used large oscillation angles of up to 30^o (optimum at 15^o to 20^o) that are considered inappropriate. It is on this ground that the current study was carried out.

Experiment. The cutting tests were conducted on a Flow International waterjet cutter on cutting 87% alumina ceramic tiles. The machine was equipped with a model 20X dual intensifier pump able to produce the water pressure of up to 380MPa and a five-axis robot manipulator for handling the cutting head. The jetting system parameters used were: orifice diameter = 0.33 mm, nozzle length = 76.2 mm and nozzle diameter = 1.02 mm. 80 mesh almandine garnet sand was used as the abrasives. Four major process parameters were considered and each was selected at 4 levels, they were water pressure (275, 310, 345 and 380MPa), traverse speed (0.67, 1, 1.33 and 1.67 mm/s), abrasive mass flow rate (6.8, 9.1, 11.3 and 13.6 g/s), and standoff distance (2, 3, 4 and 5mm). The nozzle was oscillated from its origin (i.e. normal to the work surface) towards the jet traverse direction at the combinations of 4 oscillation frequencies (2, 6, 10 and 14 Hz) and 4 oscillation angles (2, 4, 6 and 8). In addition, some cutting tests without nozzle oscillation was also conducted for comparison purpose. An orthogonal experimental design technique was used which yielded a total of 110 tests. Various quantities for the cutting performance and kerf characteristics were acquired and analyzed. Some major findings are presented in Fig. 3, where Q is abrasive mass flow rate, h is standoff distance, V is jet traverse speed, P is water pressure, F is oscillation frequency and A is oscillation angle.

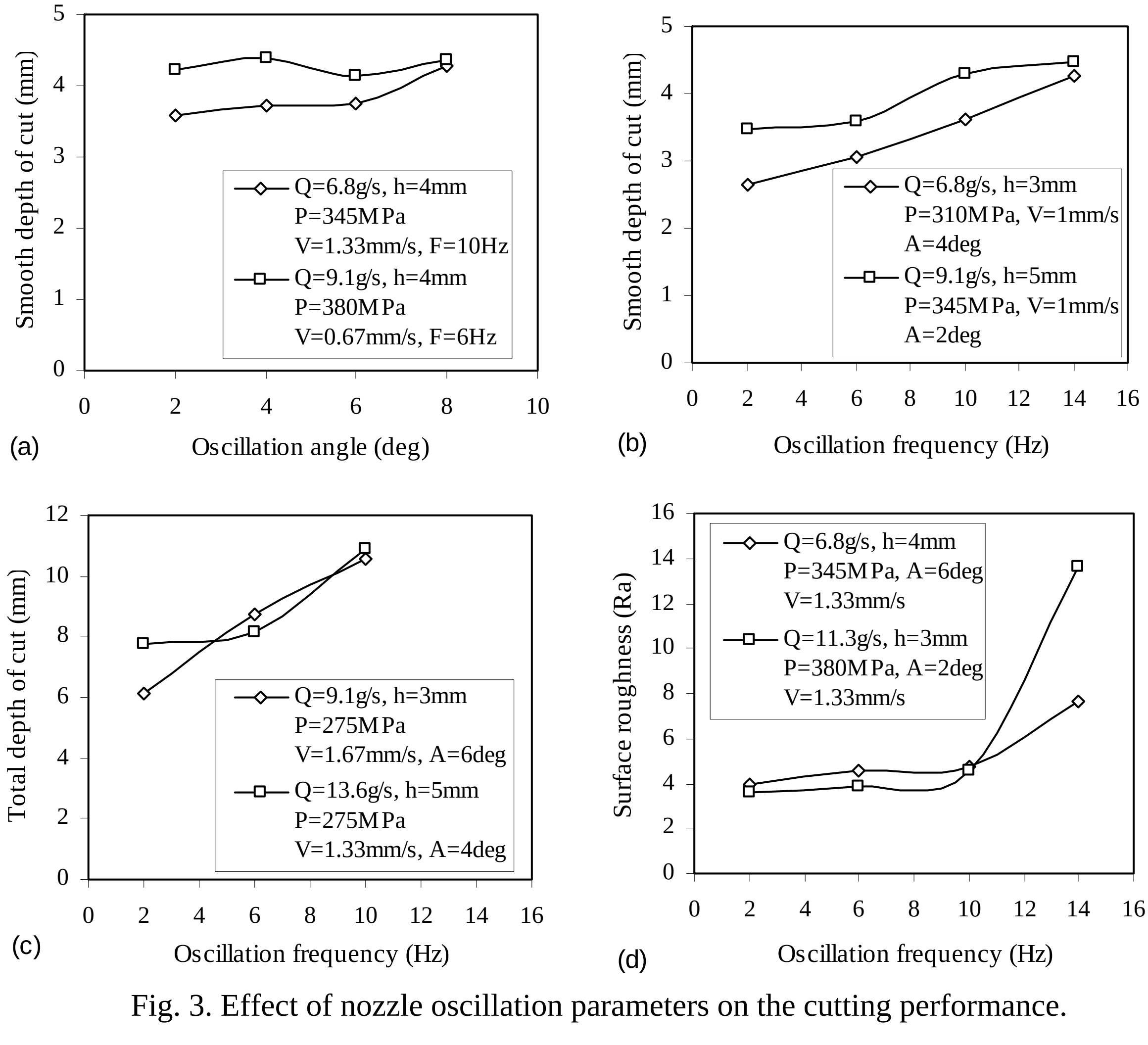


Fig. 3. Effect of nozzle oscillation parameters on the cutting performance.

Outline of major results. Analyzing the experimental data has revealed that nozzle oscillation could in fact increase or decrease the cutting performance such as total depth and smooth depth of cut. In the worst cases, improper use of nozzle oscillation has resulted in about 37% reduction in the smooth depth of cut. This adverse effect was also noticed on the total depth of cut, up to 7% reduction for the small number of cases that the experiment could produce for comparison. A further analysis has found that in general, small oscillation frequency tends to worsen the major cutting performance. For instance, most of the tests using the frequency of 2Hz reduced the total depth and smooth depth of cut as compared to the conventional cutting mode. All the tests using oscillation frequencies at or above 6Hz were found to increase the cutting performance. If the oscillation parameters were selected correctly, this cutting technique increased the total depth and smooth depth of cut by up to 82% and 102%, respectively, in this study.

The effect of oscillation parameters on the major cutting performance measures is shown in Fig. 3. It can be seen from Fig. 3(a) that oscillation angle does not have a significant effect on the smooth depth of cut. Likewise, it was found that oscillation angle does not have a significant effect on the other performance measures, although the total depth of cut is slightly lower at 6^o than at other oscillation angles while the kerf taper starts to decrease when the angle increases to above 6^o.

However, the oscillation frequency appears to have a great effect on the cutting performance as shown in Figs. 3(b) to (d). The scanning action resulting from the oscillation motion has contributed to the increase in the smooth depth of cut. However, surface roughness increases as oscillation frequency increases and becomes deteriorated when the frequency is above 10Hz. This is perhaps caused by machine vibrations enforced by the oscillation. The increase of total depth of cut with the oscillation frequency is again a result of the jet scanning action which not only clears the target surface for the subsequent particles to cut, but more importantly changes the particle attack angles that may benefit the erosion process.

Thus, nozzle oscillation at small angles can significantly improve the cutting performance if the oscillation parameters are correctly selected. From the above analysis, the oscillation frequency can be selected at 10Hz and oscillation angle may be selected at 6^o or higher and 8^o or 10^o are recommended. These oscillation parameters will result in less theoretical geometrical errors produced on the kerf profile in AWJ contouring than the earlier reported optimum oscillation parameters [5]. In addition, this study has made it clear that nozzle oscillation can have adverse effect on the cutting performance so that the oscillation parameters must be selected correctly, e.g. using the values recommended in this study.

A visualization study was carried out to uncover the underlying mechanism for nozzle oscillation to increase the depth of cut [13]. It was carried out on a transparent plexiglass. The kerf formation process and material-jet (or particles) interference were recorded by a high speed video camera and the images were then analyzed. It was found that the successive traces of particles on the cut surfaces with nozzle oscillation are steeper than those without oscillation, which results in more particle energy in the cutting direction and deeper cuts.

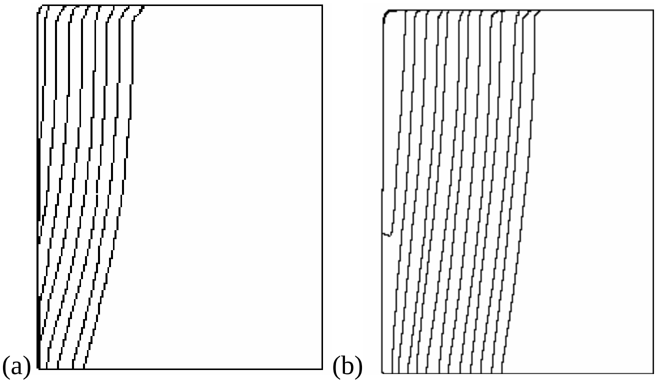


Fig. 4. Samples of abrasive waterjet-work material interface trace profile: (a) traditional cutting mode; (b) with nozzle oscillation [13].

Concluding Remarks

Although AWJ cutting is a widely accepted and increasingly used technology for processing various materials, its cutting capability has limited its application domain. The need to increase its cutting capability and cutting performance is therefore apparent. Angling the jet forwards in the cutting plane and multipass cutting operations have been proven to be effective in increasing the AWJ cutting performance, although more study and predictive models are needed for the selection of the number of passes and the cutting parameters in each pass. The controlled nozzle oscillation cutting technique presented here has been shown to be able to significantly increase the cutting performance in single pass cutting without any additional costs to the cutting process.

It has been found that if the oscillation parameters are not correctly selected, nozzle oscillation can adversely affect the cutting performance (e.g. reducing the smooth depth of cut by up to 37%) while these conditions are found at small oscillation frequencies. Furthermore, it has been shown that nozzle oscillation at small angular amplitudes is equally effective to what has been reported earlier if the oscillation and other process parameters are correctly selected.

However, the investigations on nozzle oscillation have considered only straight slit cutting. As profile cutting or contouring is a common practice in AWJ cutting, further work is required to study if and how controlled nozzle oscillation can be used in contouring, including programming the nozzle handling device. Theoretically, angling the jet results in geometrical errors on the machined profile. Quantifying these errors needs to take into account the jet tail-back effect when it cuts into the material. The existing nozzle oscillation technique makes a nozzle to oscillate in the plane of cutting which is along the “chord” of a contour profile. In addition, oscillation amplitude increases as the jet cuts into a material. Thus, unless a new nozzle oscillation technique is developed for the nozzle to oscillate along the “arc” with equal amplitude of oscillation from the top to the bottom kerf, this technique will result in shape or geometrical errors on the profile and the errors increase from the top to the bottom kerf. The small oscillation angles identified in this study can be used to minimize the theoretical geometrical errors produced in contouring by this cutting technique. Predictive cutting performance models for AWJ cutting with nozzle oscillation is being developed which will then be used to develop optimization strategies for selecting the best cutting and oscillation parameters.

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