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Enhancing the AWJ Cutting Performance by Multipass Machining with Controlled Nozzle Oscillation

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Abstract. The cutting performance in abrasive waterjet (AWJ) multipass cutting with and without controlled nozzle oscillation is presented based on an experimental investigation cutting an 87% alumina ceramic. The cutting capacity in terms of the depth of cut and the kerf geometrical features is analyzed with respect to the process variables. It is found that multipass cutting is a viable means to increase the cutting performance and application domain of this technology, while a further increase in the cutting performance can be made by using a controlled nozzle oscillation technique.

Introduction

The cutting capability of the abrasive waterjet (AWJ) machining technology in terms of the depth of cut and kerf quality has been one of the major obstructions limiting its applications to relatively thin materials. In order to process thicker materials, a low nozzle traverse speed together with a high water pressure is normally used [1]. Such a combination of process parameters is not preferred in practice from an economic point of view. In addition, there are always situations where the material thickness (or the depth of cut requirement) is beyond the AWJ cutting capability to penetrate in one cutting. As a result, several innovative cutting techniques have been developed in recent years in the authors' laboratory to enhance the cutting performance [1-8], among which multipass cutting and controlled nozzle oscillation can dramatically increase the cutting performance.

In AWJ multipass cutting, the jet or cutting head travels over the same kerf a number of times. It has been found [1-4] that multipass cutting not only increases the depth of cut, and hence increases the application domain of this cutting technology, but also improves the kerf quality. By properly selecting the number of passes and the cutting parameters in each pass, multipass cutting has been found to be superior to single-pass cutting whereby multipass cutting at high traverse speeds can achieve better cutting performance than a single-pass cutting at a low speed within the same cutting (or elapsed) time.

With the controlled nozzle oscillation cutting technique, a forward and backward pendulum-like oscillation motion of the nozzle along the cutting plane at pre-determined frequency and angular amplitude is superimposed to the nozzle traverse motion [1,7,8]. It has been found that when the cutting and nozzle oscillation parameters are correctly selected, AWJ cutting with nozzle oscillation can significantly improve the major cutting performance measures or indicators. Specifically, it can increase the depth of cut by as much as 82% as compared to normal cutting (cutting without nozzle oscillation and at a 90^o jet impact angle) [8].

Thus, it is interesting to study the cutting process and cutting performance when multipass cutting is combined with the controlled nozzle oscillation technique. In this paper, an experimental investigation is presented on the AWJ multipass cutting of an 87% alumina ceramic with nozzle oscillation. The cutting performance in terms of the depth of cut and main kerf geometrical features is analyzed with respect to the major process variables. This analysis forms the basis for the selection of appropriate process parameters in AWJ multipass cutting.

Experiment

The experiment cut 87% alumina ceramic plates of 25.4mm thickness with a Flow International AWJ cutter that was equipped with a high-pressure water intensifier able to supply a water pressure of up to 380MPa and a six-degree-of-freedom robot to manipulate the cutting head in both linear and oscillation motion.

For the purposes of this investigation, three major process variables were chosen which included nozzle traverse speed, number of passes, and water pressure for both the normal and oscillation cutting modes. In order to measure the depth of cut, the parameters were selected such that the total penetration depth was less than the material thickness. Table 1 gives the variable and constant process parameters used in the experiment. In order to evaluate the cutting performance with respect to the cutting time (or elapsed time), the same nozzle traverse speed was used for all the passes in some operations, while in others the nozzle traverse speed in one pass was selected as multiples of that in other passes in the same operation. The selections of nozzle traverse speeds in different operations were also carefully made for meaningful comparisons of the cutting performance in multipass as well as in single-pass cutting. A single standoff distance was used for all the tests, and the water pressure was not changed in any one operation because of the practical inconvenience. The oscillation parameters (oscillation angle and frequency) were selected for achieving the best overall cutting performance based on the finding in earlier studies [8]. Cutting without nozzle oscillation was also conducted for a comparison purpose. According to this experimental design, a total of 124 passes were conducted which produced 60 cuts for evaluations. The depth of cut and kerf taper for each cut were acquired from at least three measurements for analysis.

Table 1. Operating parameters used in the multipass cutting experiment.

Operating parameters	Setting
Nozzle traverse speed u [mm/s]	1, 2, 4, 6
Number of passes	1, 2, 3
Water pressure P [MPa]	275, 345
Oscillation angle θ [deg.]	4
Oscillation frequency F [Hz]	6
Initial (nominal) standoff distance [mm]	3
Abrasive mass flow rate [g/s]	9.1
Jet impact angle in normal cutting [deg.]	90
Neutral jet impact angle in oscillation cutting [deg.]	90
Nozzle diameter [mm]	0.762
Orifice diameter [mm]	0.254
Size of abrasives (garnet) [mesh number]	80

Results and Discussion

Kerf Profile. A visual evaluation of all the cuts shows that the kerfs characterizes differently after cutting by different number of passes. Fig. 1 shows some typical kerf profiles. Generally, the kerfs produced by a single-pass cutting possess similar features to those of the non-through cuts found in previous studies, i.e. the kerf is wider at the top and reduces gradually towards the bottom, so that a taper is formed. There is also an enlarged pocket at the kerf bottom owing to the jet upward deflection. After the second pass, the kerfs have a swollen portion, indicating the incomplete removal of the pocket produced in the first pass. The marks of the pockets produced in the first and second passes may still be visible on the kerf walls after the third pass cutting. In most cases, there is not a considerable pocket formed at the kerf bottom by the third pass cutting, possibly because of the deflected particles unable to take effective material removal at reduced energy. Qualitatively, there is no discernible difference between the kerfs produced by normal cutting and oscillation cutting in multipass operations.

Fig. 1. Kerf characteristics in AWJ multipass cutting with nozzle oscillation (from left to right: single, double and triple pass. u=2mm/s, P=275MPa).

Depth of Cut. An examination of the experimental data for the 64 cuts has shown that the total depth of cut increases with the number of passes, as might be expected, so that multipass cutting is an effective means to increase the AWJ cutting capability and application domain. A further increase in the depth of cut can be achieved by using the nozzle oscillation cutting technique. The experimental data show that nozzle oscillation has significantly increased the depth of cut by an average of 45.43% as compared to that in normal cutting under the corresponding cutting conditions for single-, double- and triple-pass cutting. While this may be anticipated, the result has confirmed the effectiveness of nozzle oscillation in increasing the depth of cut in single- as well as multi-pass AWJ cutting. Furthermore, it has been found that the depth of cut in each pass decreases with the number of passes. This is attributed to the increase in the actual standoff distance after the first and second pass of cutting which leads to a decreased jet energy at the point of attack and accordingly reduces the cutting ability of the jet.

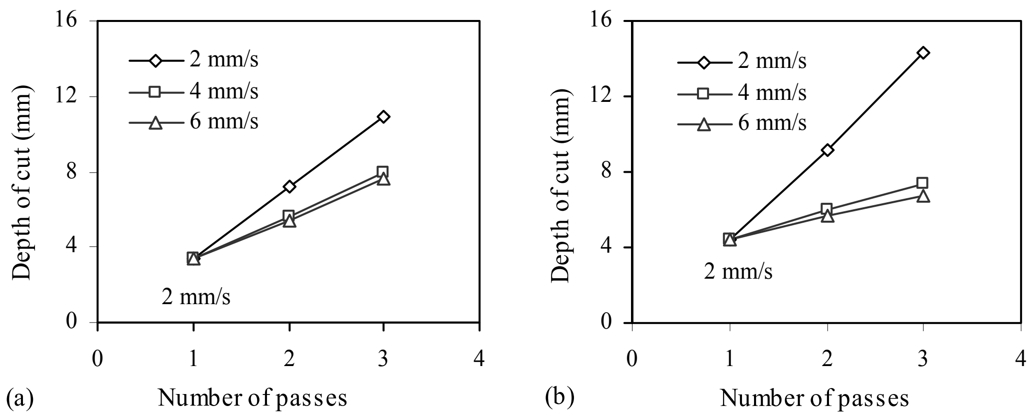

Fig. 2. The effect of number of passes on depth of cut: (a) Oscillation cutting P=275MPa, θ=4º, F=6Hz. (b) Normal cutting P=345MPa.

Fig. 2 shows the relationship between the depth of cut and the number of passes. In these cases, the nozzle traverse speed for all the first passes was 2mm/s, but different traverse speeds were used in the subsequent passes, and the speed for the second and third passes remained unchanged in each operation. While the depth of cut increases constantly with the number of passes, the slope of the curves reduces with an increase in nozzle traverse speed at the second and third passes, as a high traverse speed reduces the depth of cut in a pass as well as the total depth of cut. The general trends apply for both normal cutting and nozzle oscillation cutting, although the quantitative depth of cut values are different.

When the same traverse speed was applied for all the three passes, it is apparent from Fig. 3 that smaller traverse speeds produced larger depths of cut for single-, double- and triple-pass cutting, so that the depth vs number of passes curve for a lower traverse speed is above that for a higher traverse speed. Thus, it is possible to increase the number of passes to cut thick materials so as to increase the application domain of this cutting technology. A further increase in the total depth of cut can be achieved by using nozzle oscillation cutting and, if necessary, using lower nozzle traverse speeds. However, for a given job, the optimum number of passes and optimum cutting parameters in each pass remain to be investigated.

It is interesting to note from Fig. 3 that the depth of cut vs number of passes curves deviate as the number of passes increases, where the slope for smaller traverse speed is greater than that of higher traverse speeds. This trend applies for both normal cutting and nozzle oscillation cutting. This finding indicates that the effect of traverse speed on the depth of cut in different passes is not to the same extent in multipass cutting. It appears that the jet at lower traverse speeds can maintain better cutting capability than at higher speeds and are more effective in increasing the depth of cut in the second and third passes.

While multipass cutting coupled with the nozzle oscillation technique can be used to increase the total depth of cut and, hence, the application domain of the AWJ cutting technology, its advantage has also been found in processing materials where the required depth of cut can be achieved by a single-pass cutting. This is shown in Fig. 3 and is similar to what was reported earlier in multipass cutting without nozzle oscillation [1-4]. The dashed lines in the figure represent equal cutting time under different number of passes. It can be seen that within the same cutting time, a double-pass cutting with a higher traverse speed can produce a larger total depth of cut than that by a single-pass cutting at a lower traverse speed. Similarly, a triple-pass cutting is more effective in increasing the total depth of cut than a single- or a double-pass cutting within the same cutting time. In particular, a three-pass cutting at 6mm/s can produce a large depth of cut than a double-pass cutting at 4mm/s or a single-pass cutting at 2mm/s traverse speed for both the normal and oscillation cutting modes. From this finding, it can be deduced that a multipass cutting will need less cutting time to achieve the same depth of cut than a single-pass cutting. Moreover, if a turning maximum point of the dashed line (equal cutting speed line) exists, it exhibits the best combination of the nozzle traverse speed and the number of passes for the depth of cut curves under consideration. However, a comprehensive strategy is needed to determine the optimum number of passes and the optimum parameters in each pass for the process planning of AWJ machining.

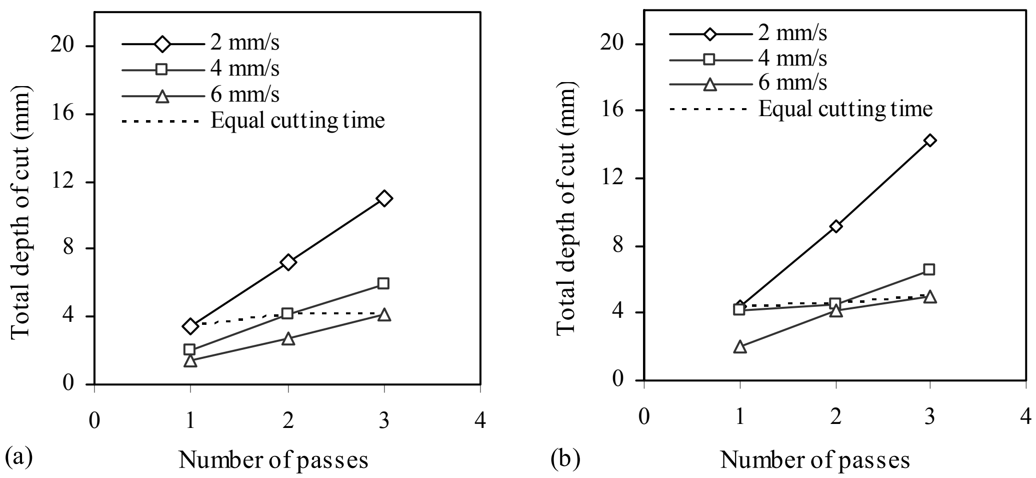

Fig. 3. The effect of traverse speed on depth of cut: (a) Oscillation cutting P=275MPa, θ=4º, F=6Hz. (b) Normal cutting P=345MPa.

Kerf Taper. The effect of number of passes and cutting parameters in each pass on the kerf taper is shown in Figs. 4 and 5. It is apparent from the figures that kerf taper decreases constantly with the number of passes, similar to what was reported earlier for cutting without nozzle oscillation [1-4]. However, the rate of kerf taper reduction decreases as the number of pass increases. This is evidenced by the flattening curves in Figs 4 and 5. As the actual standoff distance increases with the number of passes, the jet reduces its energy and cutting effectiveness, so as to remove less material from the kerf walls. As a result, its effect on the kerf taper reduces as the number of passes (or actual standoff distance) increases.

As shown in Figs. 4(a) and (b), nozzle oscillation has had a significant effect on the kerf taper in single- and multi-pass cutting. Nozzle oscillation cutting produced a much smaller kerf taper than the normal cutting mode under the same water pressure. For all the tests in this study, oscillation cutting reduced the average kerf taper from 5.43^o to 3.43^o, representing a 36.8% reduction.

Fig. 4 shows the cases where the same traverse speed was used for the first pass in all the operations, while a different speed was used in the subsequent two passes. In Fig. 5, the same traverse speed was used for all the passes in an operation. It is apparent from the figures that nozzle traverse speed significantly affects the kerf taper angle. A slow traverse speed appears to be able to reduce the kerf taper, particularly in the first and second passes of cutting. It is interesting to note from Fig. 5 that after the third pass of cutting, the difference of kerf tapers under different traverse speeds diminishes. It may be deduced from this finding that, as far as the kerf taper is concerned, higher nozzle traverse speeds may be used to increase the cutting rate without sacrificing kerf taper in multipass cutting. It is further deduced that after the third pass, the effect of nozzle traverse speed on the kerf taper becomes negligible, so that increasing the number of passes to further reduce kerf taper is not recommended from this study.

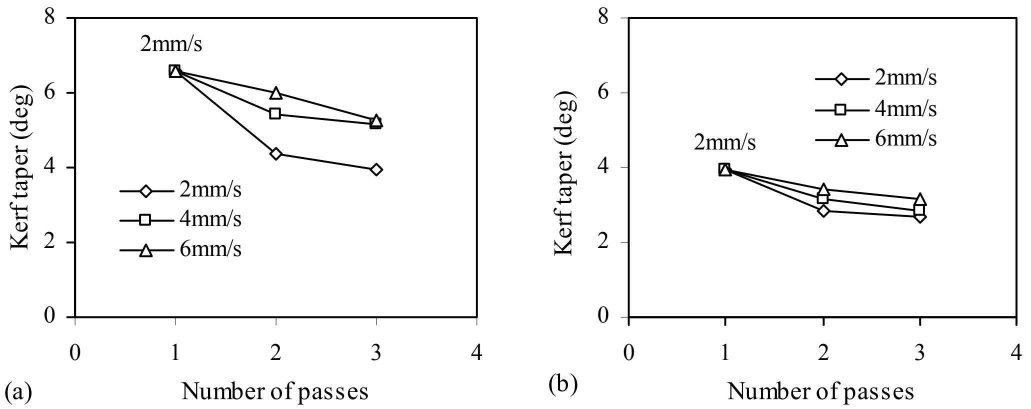

Fig. 4. The effect of number of passes on kerf taper: (a) Normal cutting P=275MPa, (b) Oscillation cutting P=275MPa, θ=4^o, F=6Hz.

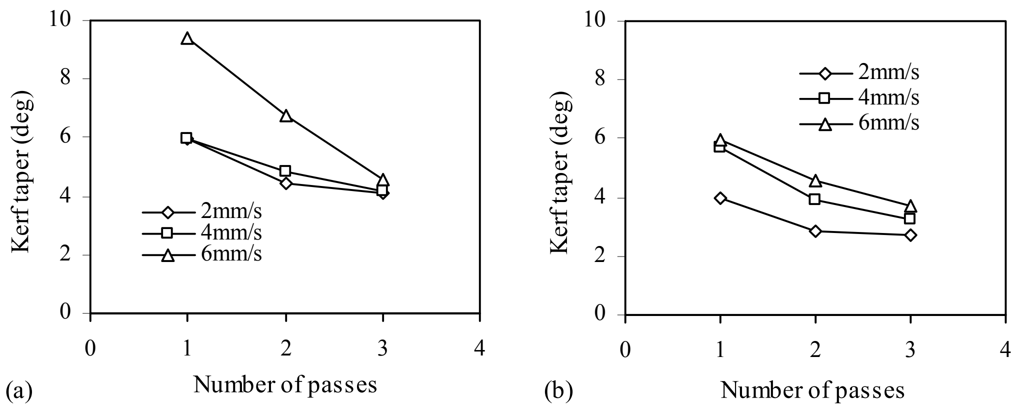

Fig. 5. The effect of traverse speed on kerf taper: (a) Normal cutting P=345MPa, (b) Oscillation cutting P=275MPa, θ=4^o, F=6Hz.

Conclusions

A study of the AWJ multipass cutting of alumina ceramics has been presented. The study was based on an experimental investigation on cutting with controlled nozzle oscillation and without nozzle oscillation (or normal cutting). Plausible trends of the depth of cut and other kerf geometrical features with respect to the major process parameters have been analyzed. This analysis has formed the basis for recommending the appropriate process parameters in AWJ cutting. It has been found that multipass cutting can significantly increase the cutting performance and application domain of this technology. A further increase of the cutting performance can be achieved by using the nozzle oscillation technique. Even for cutting relatively thin materials, multipass cutting has been found to be superior over single-pass cutting for technological and economic gains, e.g. using less time to achieve the required depth of cut than a single-pass cutting. A more comprehensive analysis of the benefits of using the nozzle oscillation cutting technique in AWJ multipass cutting will be reported shortly together with predictive mathematical models for cutting performance.

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