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Publication details:
Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science
v. 220
Chapter No. 5
pp. 703-714
0954-4062 (ISSN)

Publication Date:
2006

Publisher DOI:
http://dx.doi.org/DOI:10.1243/09544062JMES207A

Proceedings of the Institution of Mechanical Engineers
Part C Journal of Mechanical Engineering Science
Vol. 220, 2006, pp. 703-714

Profile cutting on alumina ceramics by abrasive waterjet. I. Experimental investigation

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Abstract: An experimental investigation is presented of the various cutting performance measures, such as the kerf taper and depth of cut, in profile cutting on an 87% alumina ceramic by abrasive waterjet (AWJ) over a wide range of process parameters. It is found that the taper angles on the two kerf walls produced in cutting AWJ of profiles are different in magnitude and exhibit different trends as the profile curvature radius varies. Moreover, the depth of cut increases with an increase in the curvature radius and approaches its maximum in straight cutting. The other process variables affect the cutting process in a way similar to that in straight cutting. Recommendations are finally made for the selection of process parameters in AWJ profile-cutting of alumina ceramics. Predictive mathematical models for the major cutting performance measures that are essential for the optimization of the AWJ cutting process are reported in the subsequent part of this investigation.

Keywords: Abrasive waterjet; AWJ; Profile cutting; Cutting performance; AWJ cutting.

1 INTRODUCTION

As an advanced manufacturing technology, abrasive waterjet (AWJ) cutting uses a fine jet of ultrahigh pressure water and abrasive slurry to cut the target material by means of erosion. Because of its 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**, **2**], this technology has found extensive applications in industry [**2-4**]. Since the introduction of this new cutting technology, a large amount of research and development effort has been directed towards exploring its applications and the associated science [**2**, **3**, **5**]. It has been found [**6**, **7**] that three cutting zones exist on the cut surface in processing ductile and brittle materials by an AWJ, i.e. the upper smooth zone, the lower striation zone characterized by waviness, and the jet upward deflection zone where a large pocket is formed if the jet cannot cut through the material. The study on layered composites [**8-10**] revealed similar phenomenon in terms of the cutting zones. Based on the models of Bitter [**11**] and Finnie [**12**] for particle erosion of materials, Hashish [**7**] 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 [**6**]. The geometry of the kerfs produced by an AWJ is characterized by a wider entry at the top and a narrower exit at the bottom so that a taper is produced.

Over the last decades, considerable research has been carried out to understand and improve the AWJ cutting performance, such as the kerf quality (kerf taper, surface roughness etc.), material removal rate and depth of cut or depth of jet penetration. This includes the study of the jet dynamic characteristics [**2**, **13-16**], and the analysis of the machined surfaces and kerf geometrical features to optimise the cutting process [**2**, **7**, **8**, **17-21**]. In addition, predictive models for material removal rate and the depth of jet penetration have been developed using

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the erosive theories [**7**, **18**, **22**, **23**], an energy approach [**2**, **6**, **8**], fracture mechanics [**24-26**] and by accumulating the micro-cutting processes of individual abrasive particles [**27**], although those are essentially semi-empirical models with the constants in the models determined by cutting tests. More recent studies have introduced various innovative cutting techniques to enhance the cutting performance such as controlled nozzle oscillation [**2**, **28-30**], forward jet impact angle [**2**, **8**, **31**] and multipass operations [**2**, **32**].

It is important to note that by its very nature, AWJ cutting behaves much like other cutting processes that use a "jet" or "beam" to cut. As the beam cuts into a material, it begins to lag or tail behind the entrance point of the beam at the top of the workpiece. In profile cutting, this jet tail back nature coupled with the varying jet traverse direction causes the jet to remove more material on the concave kerf wall (the outer kerf wall with larger radius), and generates different kerf tapers on the two kerf walls [**1**]. It also reduces the jet energy in the direction of jet penetration, which in turn reduces the depth of cut. However, it appears that the vast majority of research has been carried out to study the AWJ straight-slit cutting process, and there is little knowledge of the cutting performance in AWJ profile-cutting or contouring although it is a more common cutting process [**2**].

In this paper, a comprehensive experimental investigation of the cutting performance is presented when profile cutting on an 87% alumina ceramic by an AWJ. Plausible trends of the various kerf geometrical characteristics with respect to the tested process parameters are analysed. Particular attention is paid to the effect of kerf curvature on the kerf taper angles and the depth of cut. Recommendations are finally made on the selection of process parameters in AWJ profile-cutting of alumina ceramics. The mathematical models for predicting the major cutting performance measures are presented in the next part of this investigation.

2 EXPERIMENTAL WORK

The experiment was conducted on a Flow International waterjet cutter that was equipped with a model 20X dual intensifier high output pump (up to 380MPa) and a five axis robot positioning system. The specimens were 87% alumina ceramic tiles of 150×100mm dimensions and of 25.4mm thickness whose properties are given in Table 1.

Table 1 Physical and mechanical properties of the test specimens

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

It should be noted that AWJ cutting involved a large number of variables, and virtually all these variables affect the cutting results. To allow for all of them will result in unmanageable work. Therefore only the major and easy-to-control dynamic variables identified in previous studies [**2**] were considered in this experiment, i.e. profile curvature radius (or arc radius), R, nozzle traverse speed, u, water pressure, P, abrasive mass flow rate, m_a, and standoff distance between the nozzle and work surface, S_d. Water pressures were selected according to the equipment limitations and the practical range of applications. The nozzle traverse speeds were selected at appropriate spacings based on the predetermined minimum and maximum water pressures so that both through cuts and non-through cuts could be achieved. This approach would ensure that all the combinations of parameters so selected would produce at least 40% of cuts to be non-through cuts to enable the evaluation of the depth of cut in the study. Abrasive flow rates were selected based on the common applications and equipment configuration.

Thus, four levels of profile curvature radii (R=20, 40, 60, 80mm) were tested under four levels of nozzle traverse speeds (u=0.167, 0.333, 0.5, 0.667mm/s), four levels of water pressure (P=275, 310, 345, 380MPa), four levels of standoff distances (S_d=2, 3, 4, 5mm) and four levels of abrasive flow rates (m_a=7.6, 9.8, 12.1, 14.4g/s) at a 90° impact angle. Additionally, straight cutting was also conducted under the same cutting conditions for a comparison purpose. The other parameters which were kept constant included the orifice diameter (0.33mm), the nozzle diameter (1.02mm), the length of nozzle (76.2mm), the length of mixing chamber (88.9mm), and the abrasive which was garnet sand with a mesh number of 80. Using a statistical experimental design (the orthogonal arrays), a total of 104 cuts of 25mm long were performed. During the experiment, care was taken to ensure that the specimen was placed horizontally to avoid errors in measuring the tapers of the kerf walls.

A Sigma Scope 500 profile projector was used to measure the depth of cut, the top kerf width, the narrowest kerf width and the depth from the top to where the narrowest kerf width was measured for each cut. With large magnifications and micrometer readouts, this profile projector could ensure fairly accurate measurements. The kerf taper angles were then evaluated from the measured quantities. The measurement of smooth depth of cut was made by a micrometer with the assistance of a magnifier lens of a 5 time magnification and a side lighting to help distinguish the smooth cutting zone. Because of the difficulties encountered in measuring the surface roughness on the small convex and concave surfaces, this cutting quantity was not attempted in this study.

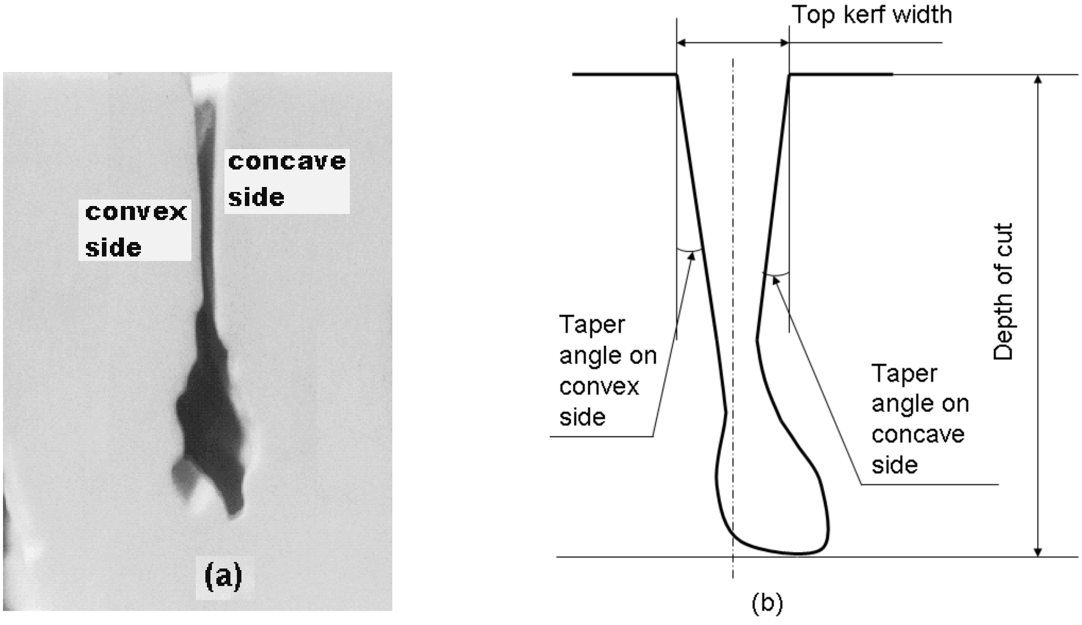

Fig. 1 Typical kerf profile and geometrical definitions

3 RESULTS AND DISCUSSION

3.1 Kerf characteristics

A visualization study on the kerfs produced has been carried out and found that two kinds of kerfs were formed depending on the cutting parameters, through cuts and non-through cuts. The cuts formed by the combination of fast nozzle traverse speeds, low water pressures and low abrasive flow rates were all non-through cuts. Typical kerf profile of a non-through cut is shown in Fig. 1(a). It has found that the overall kerf profile resembles that produced in straight cutting, i.e. the kerf is characterized by a wider entry and a narrower exit, so that there is a taper associated with the kerf walls.

As shown Fig. 1(a), the major geometrical deficiencies are the kerf taper on the kerf walls which is around 4^o to 5^o in this study. The kerf taper on the convex side of the kerf wall (the wall that is close to the arc or curvature centre with smaller radius than the concave side) is generally larger than that on the concave side. The kerf geometrical definitions are shown in Fig. 1(b). The difference between the kerf taper angles on the two kerf walls in any cut is within 1.5^o. Unlike in straight-slit cutting, the pocket formed at the kerf bottom in AWJ contouring tends to be outward to the concave side of the kerf wall as shown in Fig. 1(a).

The machined surfaces have been found to possess similar characteristics to those produced in straight cutting. Fig. 2 shows a typical case, from which it can be seen that the surface quality varies from the top to the bottom of the machined surface. Generally, the kerf has a smooth surface at the upper zone that corresponds to the cutting wear zone where the material is removed by particle impact at shallow angles according to Hashish [**7**], while the surface in the lower zone is characterized by striation or waviness corresponding to a deformation wear mode. The study found that the length of smooth cutting zone, i.e. the smooth depth of cut, increases with an increase in water pressure and abrasive flow rate, and a decrease in nozzle traverse speed. These findings are consistent with those in straight cutting.

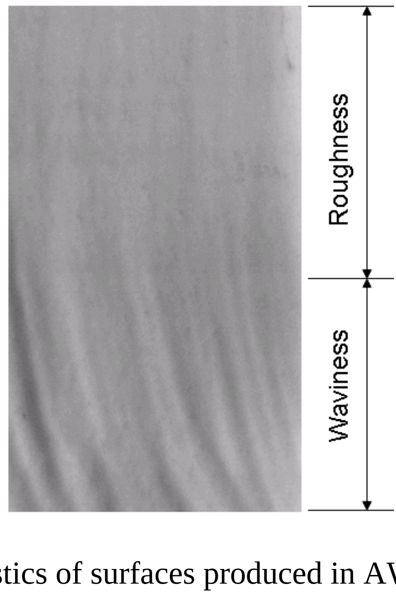

Fig. 2 Characteristics of surfaces produced in AWJ profile cutting

3.2 Effect of process parameters on the kerf taper angles

Kerf taper is a special geometrical feature inherent to all jet cutting processes. An understanding of the kerf taper with respect to the various process variables enables the minimization of this geometrical defect as well as to take correct actions to compensate for this defect in process planning.

The effect of profile curvature on the taper angles on the convex and concave side of the kerf walls under different cutting conditions is shown in Figs. 3(a) and (b). The figures again show that the kerf taper angles on the two kerf walls are not equal in value especially when cutting small curvature radii. The taper angle on the convex side of the kerf wall is larger than that in the concave side; the maximum differences between the two kerf taper angles are about 1.5^o for the conditions considered in this study. It is apparent that due to the tail back effect, the jet removes more material from the concave side of the kerf wall than from the convex side during profile cutting, thus increasing the kerf taper angle on the convex side while reducing that on the concave side. As the jet travels along a curve, the upper part of the jet can somehow follow the curved path, but not so in the lower part of the jet because of the existence of the jet tail back which increases as the jet cuts deep into the workpiece. This feature may be beneficial in contouring where only the convex side of the cut is needed to form a component. However, the increase in the kerf taper in the concave profile may require a secondary process or a compensation action to reduce the kerf taper. The figures also show that the kerf taper on the concave side increases with profile curvature radius, while a reverse trend is seen on the convex side. This is again an evidence of the effect of jet tail back on the kerf taper in contouring and that the effect is magnified as the curvature radius decreases. The difference of the kerf taper on the two kerf walls reduces as the curvature radius increases. It can be deduced that when the curvature radius is infinite, i.e. in straight cutting, these two kerf taper angles approach to the same value.

The effect of jet traverse speed on the kerf taper angles is shown in Fig. 3(c). It is evident that a higher traverse speed results in larger kerf taper angles on both kerf walls. This is because of less overlapping and cutting actions on the target material by fewer abrasive particles under high traverse speeds. It can also be noted from Fig. 3(c) that the difference between kerf taper angles on the two kerf walls tends to increase with the traverse speed. It is apparent that the jet tail back nature has a more detrimental effect on geometric differences at higher nozzle traverse speeds. Accordingly, cutting with a slower jet traverse speed is not only expected to produce more parallel cutting walls, but overcome the geometric deficiencies caused by jet tail back in AWJ contouring. Moreover, cutting with slow traverse speed is especially important for the cutting of profiles of very small curvature radii. However, low traverse speeds are not preferred in practice so that an optimum combination of the process parameters to achieve the required kerf quality needs to be considered. This analysis is an essential step towards such an optimization.

Fig. 3(d) shows the influence of abrasive mass flow rate on the kerf taper angle in profile cutting by AWJ. It can be noticed that the kerf taper exhibits a slight increase trend with the abrasive flow rate, although the influence is less significant than the other process parameters. The figure also demonstrates that the kerf tapers on the two kerf walls increase with abrasive flow rate in a similar manner. This increase trend is attributed to the erosion actions by more particles that increase the top kerf with. However, as the jet cuts into the workpiece, the energy of the particles decreases and has less effect on the kerf width than at the upper portion of the cutting front.

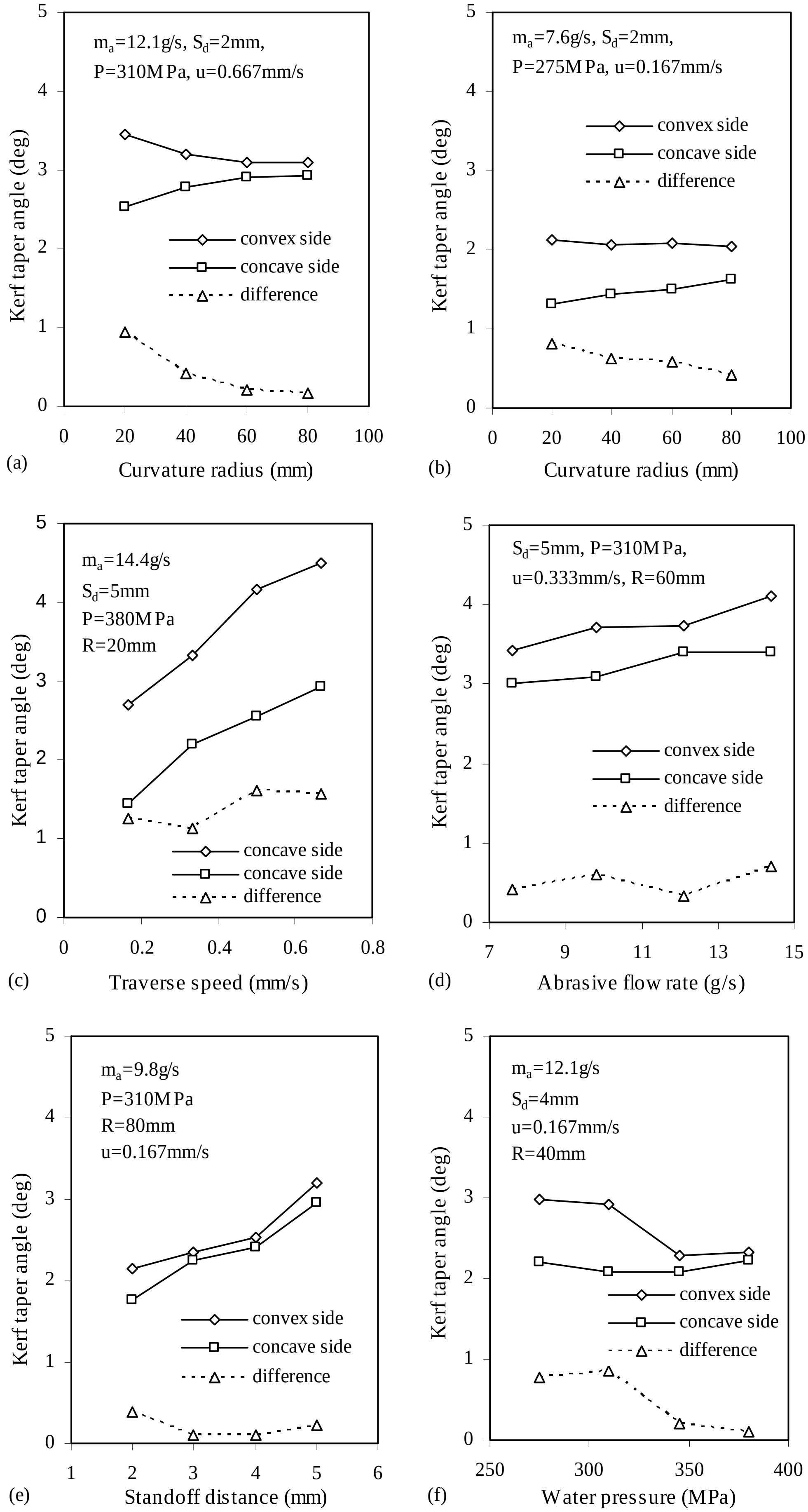

Fig. 3 The effect of process parameters on the kerf taper angles

The variation of kerf taper angle with respect to standoff distance is shown in Fig. 3(e). It can be noticed from the figure that kerf taper angles on both the convex and concave sides of the kerf walls increase with an increase in standoff distance within the range considered in this study (2-5mm). It may be explained that an increase in standoff distance resulted in an increase in the jet diameter which generated a wider entry at the top of the workpiece. However, the low jet energy in the lower cutting front did not widen the bottom kerf and might reduce the kerf width. As a result, an increase in standoff distance is associated with an increase in kerf taper angles. It can also be noticed from the figure that the standoff distance has not shown a clear trend in affecting the difference between the kerf taper angles on the two kerf walls. From a practical point of view, this finding suggests that small standoff distances are preferred for small kerf taper angles.

The effect of water pressure on kerf taper angles in AWJ profile-cutting is shown in Fig. 3(f). It is apparent from the figure that an increase in water pressure results in a decrease in kerf taper angles although the decrease on the concave side of the kerf is marginal. This may be attributed to the high pressure jet that can open a wider kerf in the lower part of the target material since the jet remains effective in that cutting region, thus decreasing the kerf taper. However, it can also be observed from the figure that the kerf taper angles on the two cutting walls show a slight increase as the water pressure is further increased. This may be an evidence of the critical water pressure identified by Hashish [**33**] beyond which the positive effect of water pressure on kerf taper angle reduces. Fig. 3(f) also shows that the differences between the kerf taper angles on the two kerf walls decreases with an increase in water pressure, possibly because of less jet lag under high water pressures.

3.3 The effect of process parameters on the top kerf width

The knowledge of kerf width variation with the process parameters in AWJ cutting is required for the control of part geometrical accuracy and for jet offset, or compensation, to achieve the required part dimensional accuracy. The typical trends for the effect of profile curvature radius on the top kerf width are plotted in Figs. 4(a) and (b). It is noticed that the effect of this parameter is not significant. This may be attributed to the fact that jet tail back usually occurs in the lower part of the workpiece; as a result, it does not have a discernible effect on the top kerf width in contouring. Thus, the effect of curvature radius on the top kerf width will not be analysed further in this study.

Fig. 4(c) shows a typical example of the effect of traverse speed on the top kerf width. The figure reveals that in profile cutting, the top kerf width decreases with an increase in traverse speed, which is consistent with the findings in straight cutting. This can be explained that a fast traverse speed allows less abrasive particles to strike on a given target material, generating a narrow slot. However, it should be realised that high traverse speeds result in an increase in kerf taper in addition to their effect on the cutting rate and depth of cut, so that a compromised or optimum traverse speed needs to be considered when selecting cutting conditions.

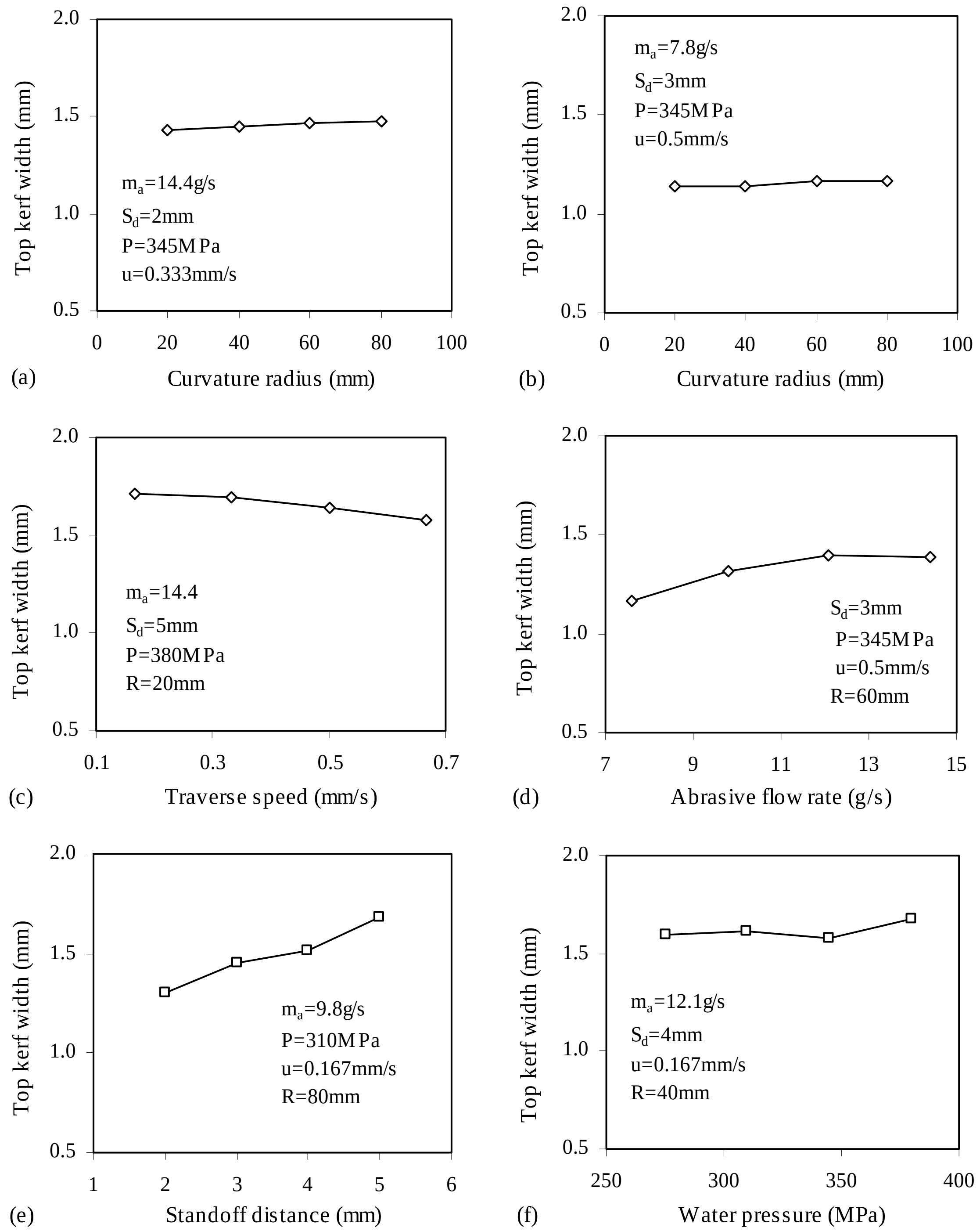

Fig. 4 The effect of process parameters on the top kerf width.

The effect of abrasive flow rate on the top kerf width is shown in Fig. 4(d). It can be seen that an increase in abrasive flow rate results in an increase in the top kerf width in contouring. This is because a higher abrasive flow rate provides more particles to strike on the target material and opens a wider slot. A higher abrasive flow rate may also increase the size (diameter) of the AWJ which opens a wider slot. It is interesting to note that the rate of increase of the top kerf width reduces as abrasive flow rate increases to beyond a certain value. This is possibly caused by the increased interference between particles as the abrasive flow rate increases, which reduces the overall cutting efficiency of particles. The above discussion suggests that while low abrasive flow rate may generate a narrow slot, it may also reduce the surface quality and the depth of cut. Thus due consideration should be given to the selection of abrasive flow rate in profile cutting, taking into account all the performance measures and job requirements.

Fig. 4(e) shows the effect of standoff distance on the top kerf width in AWJ contouring. It can be noticed from the figure that an increase in standoff distance is associated with an increase in the top kerf width. The jet spreads out as it flows away from the nozzle (or an increase in standoff distance) may be the reason for this trend. This jet spread-out results in an increase in jet diameter and hence widens the slot. From this study, short standoff distances are recommended if a narrow slot is the primary job requirement.

Fig. 4(f) shows the effect of water pressure on the top kerf width. The results indicate that the effect of water pressure on the top kerf width is not significant. It is known that the most important factor that affects the top kerf width is the effective jet diameter. The increase of water pressure does not cause a significant increase in the jet effective diameter within the small standoff distance from the nozzle exit to the work surface, and therefore does not result in any obvious variation in top kerf width.

3.4 Effect of process parameters on the depth of cut

The depth of cut, or the depth of jet penetration, is an important cutting performance measure in AWJ machining. A thorough understanding of the effects of the various process parameters on this performance measure is essential for the selection of the parameters such that maximum cutting rate and minimum cost are achieved for a given job. The effect of profile curvature radius on the depth of cut is shown in Fig. 5(a). It can be seen that the depth of cut increases with an increase in the curvature radius. It is believed that this increase is related to the jet tail back nature. As a jet cuts into the lower part of a workpiece, the jet begins to lag. When the jet travels along a curve, the jet changes its direction towards the outer or concave kerf wall at the lower part of the cutting front, and removes more materials from that kerf wall but reduces the depth of cut. From this trend, it can be deduced that the depth of cut increases with the curvature radius and approaches its maximum in straight cutting, as noticed from the experimental data in this study. It follows that if the other cutting parameters are not changed during a cutting process, a process plan to cut through a workpiece with a profile of variable curvatures should be made based on the smallest profile curvature radius.

Fig. 5(b) shows that the depth of cut decreases with an increase in traverse speed in AWJ contouring. An increase in traverse speed results in fewer particles impacting on the target material and hence less material removed so that the depth of cut is reduced. In practice, decreasing nozzle traverse speed may increase the depth of cut, but this should be the last resort after all other parameters have been optimised, since nozzle traverse speed is directly related to the cutting rate and cost.

The present study has found that the effect of standoff distance on the depth of cut is not significant, as shown in Fig. 5(c). This may be due to the small range of standoff distance (2 to 5mm) considered in this study. With the small variation of the standoff distance, the jet energy does not dissipate significantly so that the influence of this variable on the depth of cut is not discernable. As the range of standoff distance considered in this study reflects that used in practice, the selection of this parameter is not important as far as the depth of cut is concerned, so that its selection may be made based on the other cutting performance measures.

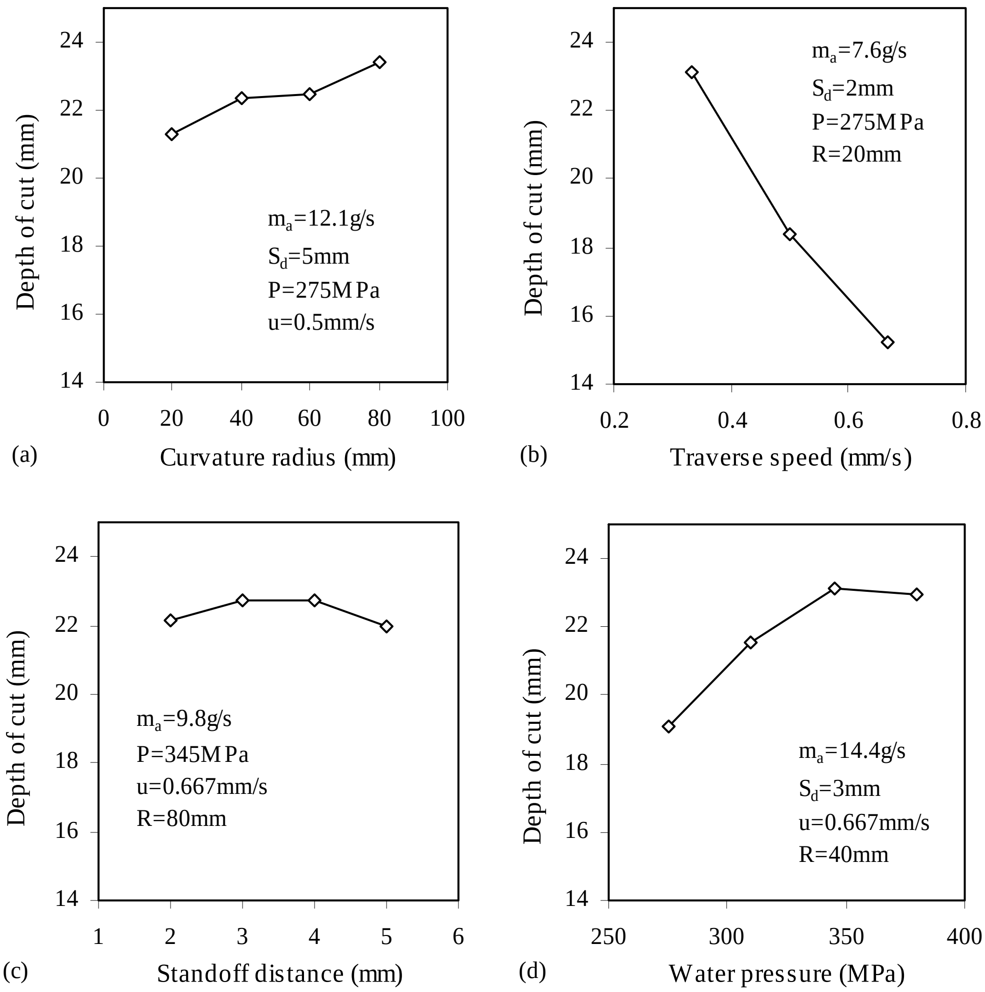

Fig. 5 The effect of process parameters on the depth of cut.

Fig. 5(d) shows that the depth of cut increases with an increase in water pressure. This is attributed to the fact that abrasive particles gain high velocity and energy when water pressure is high. High energy particles can remove more material so that the depth of cut increases. However, the increasing rate of the depth of cut with water pressure reduces as the water pressure further increases to beyond a value, as shown in Fig. 5(d). This phenomenon is an evidence of the existence of a critical water pressure identified by Hashish [**33**]. The increased particle fragmentation and interference at high water pressure levels reduces the cutting efficiency which in turn results in a reduced positive effect of water pressure on the depth of cut.

The experimental work did not produce sufficient data to examine the effect of abrasive flow rate on the depth of cut. However, from the earlier studies on AWJ straight cutting [**2**], it can be deduced that an increase in the abrasive flow rate will increase the depth of cut in a similar way to straight cutting. A statistical analysis of the experimental data and the predictive models to be presented in the second part of this investigation have confirmed this effect.

3.5 Effect of process parameters on the smooth depth of cut

As discussed earlier in this paper, the surfaces produced by AWJ are characterised by an upper smooth zone and a lower wavy zone. In some applications, the depth of the smooth zone (or the smooth depth of cut) needs to be achieved over the entire workpiece thickness, so that an understanding of the effects of various process variables on this performance measure is required for process planning.

Figs. 6(a) and (b) show that the smooth depth of cut is almost independent of the curvature radius of a cutting profile. Although jet tail back affects the total depth of cut in AWJ contouring, the effect occurs only at the lower part of the cutting front where the jet energy is reduced. As the jet produces the smooth cut zone at the upper region where the jet energy is high, it is understandable that curvature radius does not affect the smooth depth of cut. Furthermore, the plots for the smooth depth of cut on the convex kerf wall and concave kerf wall almost fall in a single curve, suggesting that the jet produces the same smooth depth of cut on the both kerf walls in profile cutting. This finding again indicates that jet tail back has little effect on the smooth depth of cut in AWJ contouring.

Fig. 6(c) shows that the smooth depth of cut decreases with an increase in traverse speed. As the nozzle traverse speed increases, the number of particles that impinge a given area on the target material reduces and, therefore, there are fewer particles involved in the erosion action, resulting in a decrease in the smooth depth of cut. As shown in the figure, the smooth depths of cut on the two kerf walls are almost identical for the same reason discussed earlier. It can also be noticed that the rate of decrease for the smooth depth of cut decreases as the traverse speed is further increased to beyond a certain value. This may be attributed to the reduced particle interference and fragmentations as traverse speed increases, increasing the cutting efficiency of individual particles.

Fig. 6(d) plots the relation between the smooth depth of cut and abrasive flow rate in AWJ profile-cutting. It shows that the smooth depth of cut slightly increases with an increase in abrasive flow rate. This is attributed to the fact that an increase in abrasive flow rate results in more particles impinging on the target surface, increasing the depth of smooth zone. However, it can be noticed that the relationship between the smooth depth of cut and abrasive flow rate is not quite linear, and the effect of abrasive flow rate decreases as it increases. This is again due to the increased particle fragmentation and interference as the abrasive flow rate increases, which reduces the cutting efficiency of individual particles [**34**]. The findings indicate that the selection of high abrasive flow rate can improve this cutting performance measure; however there is a critical value beyond which the increase in this parameter may not give further benefit, but increase the cost of the process.

From an earlier analysis in this paper, standoff distance does not have a discernible effect on the total depth of cut. However, from the data plotted in Fig. 6(e), it is noted that within the range of standoff distance tested, the smooth depth of cut exhibits a slightly increasing trend with this parameter in AWJ contouring. This phenomenon may be explained as follows. A jet may be more turbulent as it exits the nozzle, and is gradually stabilized as the jet continues to flow. The stabilized jet not only cuts the material at small wavelengths of surface irregularities (characterised by surface roughness), but it may also change the particle impact angle favourable for cutting wear mode that generates a smooth surface. Therefore, a slight increase in the standoff distance in fact increases the smooth depth of cut.

The experimental data plotted in Fig. 6(f) illustrate that the smooth depth of cut increases with an increase in water pressure in AWJ contouring. This is because of the high water pressure that offers high energy to the jet for high particle velocity, thus increasing the smooth depth of cut. However, the smooth depth of cut does not always increase linearly with the water pressure and the rate of increase reduces as noticed for many cases in this study. This phenomenon occurred mostly in the cases where high abrasive flow rates were used. Similar to the effect on total depth of cut, particle-to-particle interference and the resulting particle fragmentation may be the reason for the decreasing rate of increase in the smooth depth of cut. It is also noticed from the figure that the smooth depth of cut on the two kerf walls almost fall into a single curve. This is another evidence that curvature radius has little effect on the smooth depth of cut in AWJ contouring.

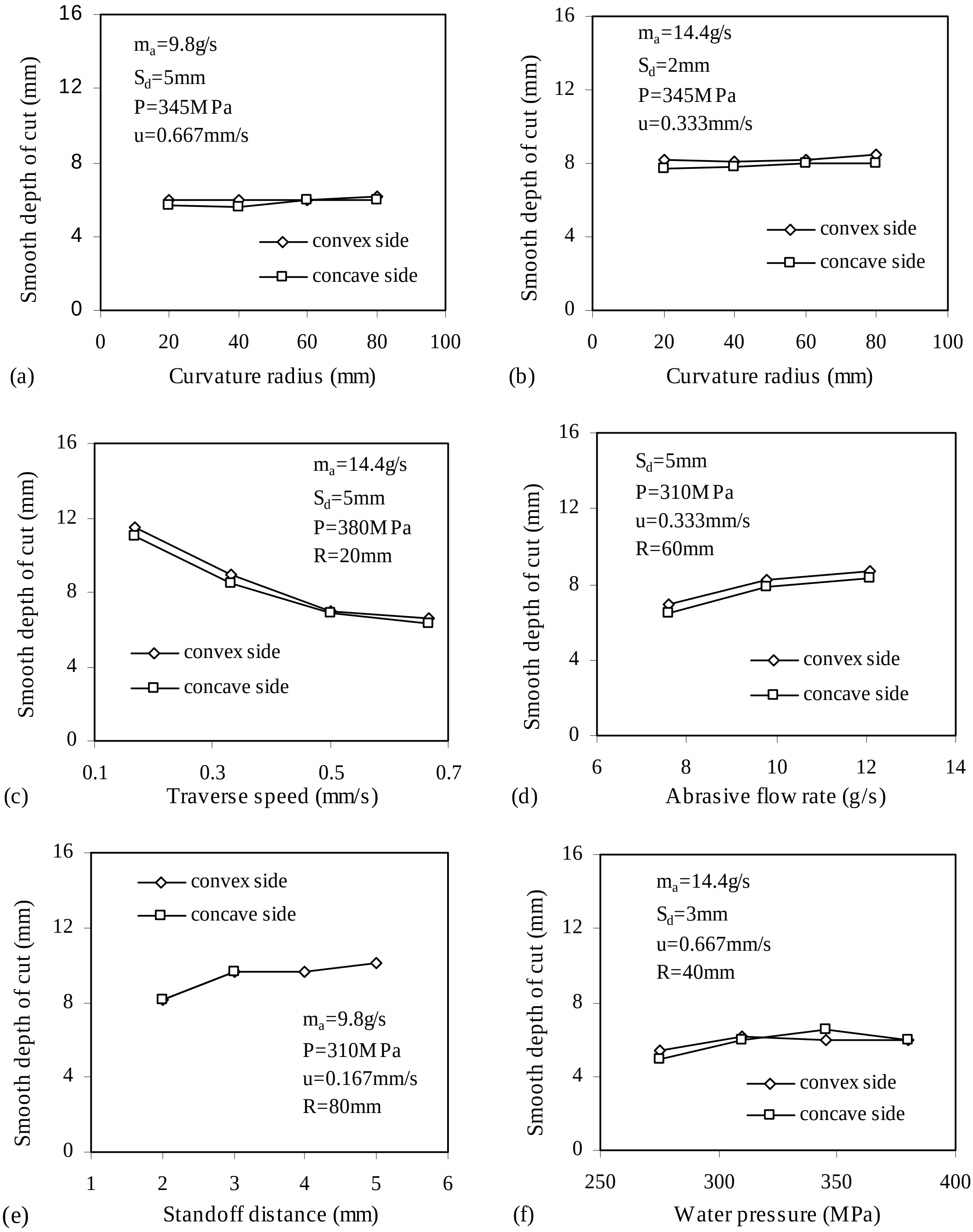

Fig. 6 The effect of process parameters on the smooth depth of cut.

3.6 Cutting parameter selection consideration

In order to evaluate the overall characteristics of the kerfs generated in profile cutting by an AWJ, the above analyses and trends are summarized in Table 2, where the "increase" and "decrease" indicate the increasing and decreasing trends of the respective quantity. It can be seen from the table that the variation of profile curvature radius affects the kerf taper and depth of cut in profile cutting; however, its effect on the top kerf width and smooth depth of cut is not significant (and not discernible). It follows that the jet tail back nature only affects the output parameters related to the lower part of the cutting front, such as the depth of cut and kerf taper angle.

It has also been found that the water pressure, abrasive flow rate, standoff distance and nozzle traverse speed affect the profile cutting process in a similar way to that in AWJ straight cutting. Since a fast nozzle traverse speed results in fewer particles impacting the target material, the top kerf width, depth of cut and smooth depth of cut all decrease with an increase in traverse speed, while kerf taper angle increases with the nozzle traverse speed. All the kerf characteristic quantities considered in the current study have been found to increase with an increase in the abrasive flow rate. An increase in abrasive flow rate can improve the smooth depth of cut, but produces a wide entry on the top of the kerf. Kerf tape angles showed a slight increase with an increase in abrasive flow rate and this effect may be neglected in practice. The effect of standoff distance on the depth of cut is not discernible from this study. However, large standoff distances were found to increase kerf taper and top kerf width. High water pressures were found to reduce the kerf taper and increase the smooth and total depth of cut, but its effect on the top kerf width is minimal in this study.

Table 2 Effect of process parameters on the cutting performance in AWJ profile cutting

	Curvature radius	Traverse speed	Abrasive flow rate	Standoff distance	Water pressure
Kerf taper (convex side)	increase	increase	increase	increase	decrease
Kerf taper (concave side)	decrease	increase	increase	increase	decrease
Top kerf width	not significant	decrease	increase	increase	not significant
Depth of cut	Increase	decrease	increase	not significant	increase
Smooth depth of cut	not significant	decrease	increase	increase	increase

The above trends suggest that the selection of process parameters in AWJ profile-cutting or contouring should be based on the specific job requirements. If the profile curvature is constant, a combination of high water pressure with an appropriate low traverse speed is recommended to achieve the depth of cut. When a job requires more parallel kerf walls, i.e. to produce small kerf taper angles, high water pressure and short standoff distance are suggested together with suitably slow nozzle traverse speed. When cutting small curvature radii, low nozzle traverse speed is recommended to reduce the geometric deficiency. To increase the smooth depth of cut, a combination of low nozzle traverse speed, high water pressure and high abrasive flow rate is recommended. It appears from these analyses that cutting rate and process cost are often compromised in order to meet the job requirements. The process parameters can be optimized so as to maximize the cutting rate and minimize the process cost with reliable predictive cutting performance models that are presented in the second part of this investigation.

In practice, it is possible to side-angle the nozzle in the direction normal to the profile to compensate for the inclination of one of the two kerf walls. However, the compensation angle has to be changed constantly with the profile curvature when cutting a profile with variable curvature (including convex and concave curvatures), in addition to the variation of the direction of the compensation angle. This requires a comprehensive motion control system to manipulate the cutting head, which warranties a future investigation.

In addition, the study has shown that a decrease in profile curvature radius is associated with a decrease in the depth of cut. However, during an AWJ cutting process, it is not expected that other process parameters, particularly the water pressure and abrasive flow rate, be changed according to the profile curvature to achieve the same depth of cut. Thus, process planning in such cases should be made based on the smallest profile curvature radius in order to cut through a workpiece of variable profile curvatures.

4 CONCLUSIONS

An experimental investigation of profile cutting on 87% alumina ceramics by AWJ has been presented. Plausible trends for the various cutting performance measures with respect to the major process parameters have been analysed, which has provided an in-depth understanding of the cutting process. It has been found that the kerfs produced in profile cutting are similar to those in AWJ straight cutting. However, the kerf tapers on the two kerf walls are no longer of equal value. The kerf taper on the convex side of the kerf wall increases with a decrease in the curvature radius of the cutting profile, while a reverse trend applies for the kerf taper in the concave side. The study has also found that the depth of cut increases with an increase in the curvature radius and approaches its maximum in straight cutting. Based on this study, recommendations have been made for the selection of process parameters in process planning. In order to optimize the AWJ cutting process for the maximum technological and economic benefits, it is essential that predictive models for the various cutting performance measures be developed, which is presented in the second part of this investigation.

ACKNOWLEDGEMENTS

The authors wish to thank the Australian Research Council (ARC) for financial support to this and other projects.

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