A machinability study of polymer matrix composites using abrasive waterjet cutting technology

Author:
Wang, Jun

Publication details:
Journal of Materials Processing Technology
v. 94
Chapter No. 1
pp. 30-35

Publication Date:
1999

Journal of Materials Processing Technology, 94/1(1999), pp. 30-35.

A machinability study of polymer matrix composites using abrasive waterjet cutting technology

Jun Wang
School of Mechanical, Manufacturing and Medical engineering,
Queensland University of Technology,
GPO Box 2434, Brisbane, Qld. 4001, Australia.
Fax: (+61.7) 3864 1469,
Email: j.wang@qut.edu.au

Abstract
Abrasive Waterjet (AWJ) cutting is an emerging technology for material processing with the distinct advantages of no thermal distortion, high machining versatility, high flexibility and small cutting forces. In this paper, an experimental investigation of the machinability and kerf characteristics of polymer matrix composite sheets under abrasive waterjets is presented. It shows that this unique 'cold' cutting technology is a viable and effective alternative for polymer matrix composite processing with good productivity and kerf quality. Plausible trends of kerf quality with respect to the input parameters are discussed, from which recommendations are made for process control and optimization.

Keywords: Abrasive Waterjet Cutting, Composite processing, Machinability, Kerf characteristics.

1. Introduction

Polymer matrix composites are being increasingly used in various applications due to their superior physical and mechanical properties. However, there are a number of problems associated with the processing of these kinds of materials. Traditional processing methods such as band saw cutting result in not only low cut quality but also low productivity, while the non-traditional Laser cutting technology has been found to yield large burr formation, dimensional inaccuracy due to thermal distortion, heat affected zone (or burnt), and even fire hazard for these heat sensitive materials [1]. The unique 'cold' Abrasive Waterjet (AWJ) cutting technology, due to its distinct advantages of no thermal distortion, high machining versatility, high flexibility and small cutting forces [2], offers great potential for the processing of polymer matrix composites. While considerable amount of work has been reported on the investigation of Abrasive Waterjet cutting of various materials such as metals and ceramics [3-7], including the studies of the mechanism of Abrasive Waterjet cutting process, modeling for process control and optimization as well as the techniques to enhance the cutting performance of Abrasive Waterjets [3,5,8-12], the study on the processing of polymer matrix composites using AWJ cutting technology has received little attention [13], despite the increasing use of these materials in practice.

In this paper, the machinability of polymer matrix composites under abrasive waterjets is studied based on an experimental investigation. A visualization study is carried out to evaluate the microscopic features of the cut surfaces and the machinability of the materials.

This is followed by a statistical analysis of the experimental data to examine the kerf characteristics as assessed by kerf geometry (kerf width and taper) and surface quality, from which recommendations are made on selecting the optimum combination of the process parameters for practical applications.

2. Experimental set-up and procedure

The experiment was conducted on a Flow Systems International waterjet cutter equipped with a model 20X dual intensifier high output pump (up to 55,000 psi or 380 MPa) and a five axis robot positioning system to cut 300x300 mm test specimens. The specimens were 3 mm polymer based matrix compound being reinforced with teflon fabric using phenolic resin. Some of the major mechanical and thermal properties of the specimen are given in Table 1.

Table 1. Major properties of the test material.

Impact strength	315 MPa
Compressive strength (flatwise)	185 MPa
Compressive strength (edgewise)	1.6 MPa
Shear strength	100 MPa
Maximum working temperature	130°C

Although AWJ cutting involves a large number of variables, as noted by Hashish [3], and virtually all these variables affect the cutting results, only the major and easy-to-adjust variables were considered. These included the water pressure, the nozzle traverse speed and the stand-off distance between the nozzle and the workpiece. As such, the water pressures within the common ranges of application and the equipment limit were tested at five levels from 30,000 psi to 50,000 psi at an increment of 5,000 psi. For each level of the water pressure, four levels of nozzle traverse speeds (1,000, 1,200, 1,500 and 1,800 mm/min) and four levels of stand-off distance (2, 3, 4 and 5 mm) were used at a single level of abrasive flow rate of 0.36 kg/min and a single level of impact angle of 90°. The other parameters were kept constant using the system standard configuration, that is, the orifice diameter was 0.41 mm, the mixing tube diameter was 1.27 mm, and the length of mixing tube was 88.9 mm. The abrasives used was almandite garnet sand with a mesh number of 80. Thus, a total of 80 straight cuts (slits) of about 100 mm length were carried out.

The approach to selecting the appropriate levels of traverse speed was such that at the predetermined maximum stand-off distance and minimum water pressure, the traverse speed was adjusted in actual operations to allocate the maximum traverse speed allowed for a through cut. Other traverse speeds were accordingly selected at an appropriate spacing. Since it has been known that the penetration depth of abrasive waterjet increases with an increase in the water pressure and a decease in the stand-off distance [12], this approach could ensure that all the combinations of the parameters so selected would produce through cuts for evaluation. It should be noted that higher traverse speed may be possible at higher water pressures, but this will result in negative effect on the kerf quality, as noted in the experiments and reported in the paper. In addition, it has been known that water pressure will be less effective if beyond a certain critical value [6,7]. It is therefore believed that the selected range of nozzle traverse speeds was reasonable both practically and fundamentally.

3. General assessment of machinability

An observation study on all the cuts has revealed that AWJ produced clean slits of much higher quality than other processes such as band saw and laser cutting [1] and the productivity was comparable to the laser cutting process. The kerfs can be represented by Figure 1 where the top kerf is commonly wider than the bottom as a unique feature of jet cutting technology. Burrs were noticed at the jet exit side (bottom kerf) on some of the cuts due to the material deformation when low water pressure and high traverse speed were used. However, the burrs formed in AWJ cutting were found to be much smaller than the burrs formed in band saw and laser cutting and could be easily removed. Therefore, burr formation is not a major concern in AWJ cutting of the test material.

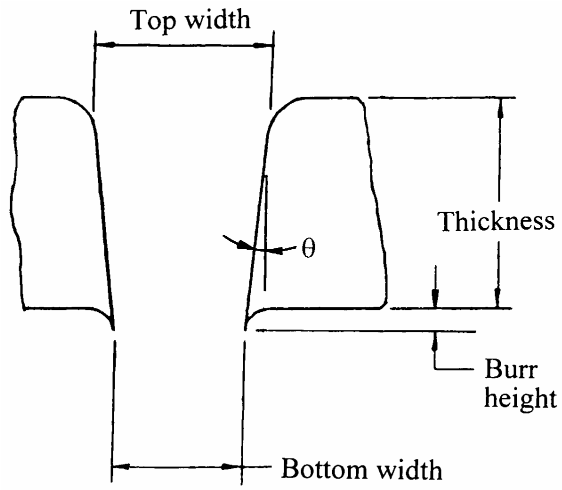


Figure 1. Schematic and definition of kerf geometry.

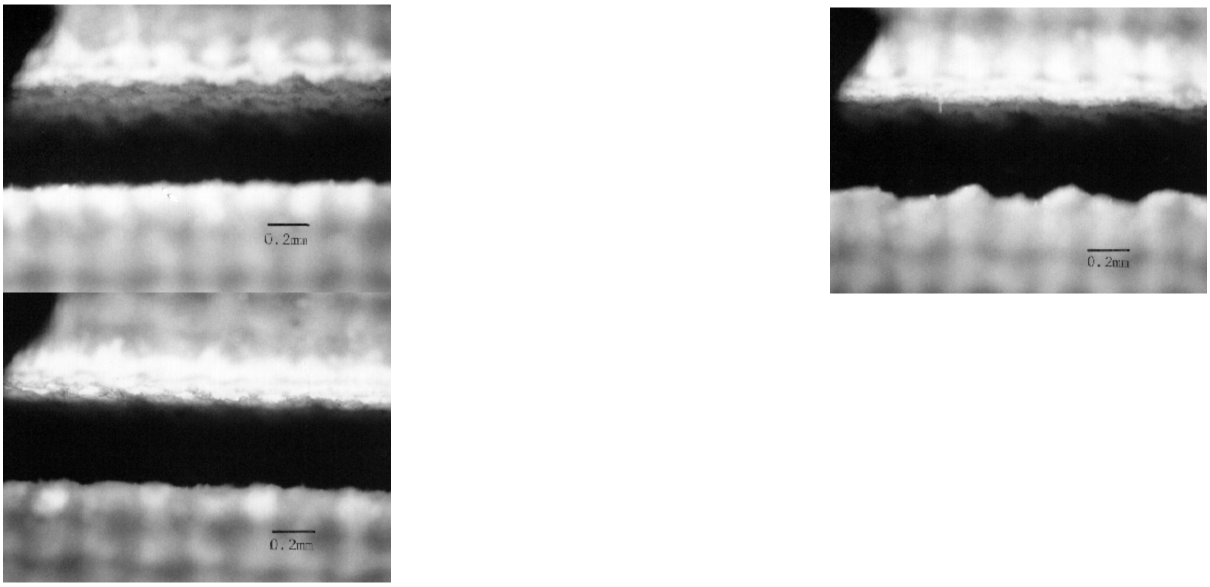
Some representative cuts were examined under an 'Olympus' stereo microscope to evaluate the microscopic features of the waterjet machined surfaces. At 20x magnification, no significant irregularity was observed in any of the examined cut surfaces although striations exist on some of the cuts, typically at the lower portion of the cut surfaces. As expected for this 'cold' cutting process, no heat affected zone was noticed on any cut surfaces. Microscopic observations were also made under the Scanning Electron Microscope (SEM) to study the cutting mechanisms and the features of the machined surfaces at 200x to 300x magnifications. This again showed that AWJ can produce clean and good quality cut surfaces. Consequently, AWJ cutting is a viable and alternative technology for polymer matrix composite processing with good cut quality and productivity.

4. Kerf characteristics

4.1 Effect of cutting parameters on surface quality

It has been reported [6] that the topography of an AWJ cut surface may be divided into a microscopic (roughness) component at the upper so-called cutting wear zone and a macroscopic (striation or waviness) component at the lower deformation wear zone. While surface roughness is a common phenomenon in all machining, striation or waviness is a special feature of cuts with beam cutting technology, such as AWJ cutting. It is formed when the ratio between the available energy of the beam and the required energy of the destruction becomes comparatively small [14]. In AWJ cutting, the cutting power of the jet decreases from the top to the bottom of the cut surface and striations are formed at the lower portion of the cut surfaces. Thus, surface roughness and striation characteristics have formed the criteria to evaluate the quality of AWJ cut surfaces.

These characteristics of the cut surfaces was noted in the current study and confirmed by a SEM analysis of selected samples. It has been found that while some cuts show clear patterns of roughness and striations, others appear to be dominated by either roughness or striation due to the large ranges of water pressure and traverse speed used. This result has made quantitative analysis difficult. In general, the cut surface may be characterised by roughness when high water pressure and low traverse speed are used. Conversely, at low water pressure and/or high traverse speed, striation becomes the main feature of the cut surface.



(a) stand-off distance = 4 mm
water pressure = 30,000 psi
speed = 1800 mm/min

(b) stand-off distance = 4 mm
water pressure = 40,000 psi
speed = 1800 mm/min

(c) stand-off distance = 4 mm
water pressure = 40,000 psi
speed = 1200 mm/min

Figure 2. Illustrations of kerf quality under Abrasive Waterjets.

Figure 2 gives three microphotographs showing some typical trends of the peak-to-valley height (or amplitude) for either surface roughness or striation in terms of the process variables. It has been found that based on the results taken at close to the top edge of the kerfs, the surface roughness or striation amplitude increases with an increase in the water pressure, as evidenced in Figures 2(a) and (b). These microscopic photographs show that for the cutting conditions used, the maximum peak-to-valley height increased from about 20μm to about 70μm when the water pressure increased from 30,000 psi to 40,000 psi. This may be due to the fact that, at the same traverse speed, increased jet pressure causes more energy disbursement from the abrasives in the area bombarded by the atomized waterjets, resulting in locally widened kerf. It is also believed that at higher water pressure, the dynamic behaviour of the waterjet will contribute more to the surface striation as the energy fluctuation increases with an increase in the water pressure. However, a further quantitative study is required to examine the surface characteristics in terms of surface roughness and striation, respectively, under varied water pressure.

It may be anticipated that an increase in the traverse speed is associated with an increase in the surface roughness and the amplitude of striation, since higher traverse speed allows less overlapping machining action on the cut surface [5] and fewer abrasive particles impinging the surface. The experimental data in this study follow this trends, as indicated in Figures 2(b) and (c). By contrast, the effect of stand-off distance on the surface roughness and striation is hardly discernible.

4.2 Effect of cutting parameters on kerf geometry

Kerf geometry is a characteristic of major interest in abrasive waterjet cutting. As shown in Figure 1, abrasive waterjets will generally open a tapered slot with the top kerf W_t being wider than the bottom kerf W_b, and kerf taper or kerf taper angle θ is normally used to represent this characteristic.

In the present work, the top and bottom kerf widths for all the cuts were measured with a "Carl Zeiss" universal measuring microscope. Three measurements were taken for each cut at the segment away from the ends of the slots to eliminate the effects of waterjet entry and exit of the cutting process, from which the average reading was taken as the geometrical values. The kerf taper angle θ was then calculated using the measured values of the top and bottom kerf widths for each cut based on the equation $\theta = \tan^{-1}[(W_t - W_b)/(2\ t)]$, where t is the material thickness.

Figures 3 to 5 show some typical and representative trends and relationships between the kerf geometry (top kerf width W_t, bottom kerf width W_b and kerf taper angle) and the cutting parameters. It can be noted from Figure 3 that both the top and bottom kerf widths increase approximately linearly with the water pressure, as higher water pressure results in greater jet kinetic energy impinging onto the material and opens a wider slot. The kerf taper angle also increases with the water pressure. This is because the bottom kerf width is not increased in the same order as the top kerf width, as indicated in the figure. It follows that as the jet loses its kinetic energy, it cannot remove the material adequately at the lower section, resulting in a narrow bottom kerf.

The effect of traverse speed on the top kerf width, bottom kerf width and kerf taper is shown in Figure 4. It can be seen from the figure that the traverse speed has a negative effect on both the top and bottom kerf widths, while the kerf taper angle appears to be independent of the traverse speed although the overall statistical results show that the taper angle decreases slightly with an increase in the traverse speed. The negative effect of the traverse speed on both the top and bottom kerf widths is due to the fact that a faster passing of abrasive waterjet allows fewer abrasives to strike on the jet target and hence generates a narrower slot. The nearly stabilised kerf taper is the result of the comparable rate of decreasing for the top and bottom kerf widths.

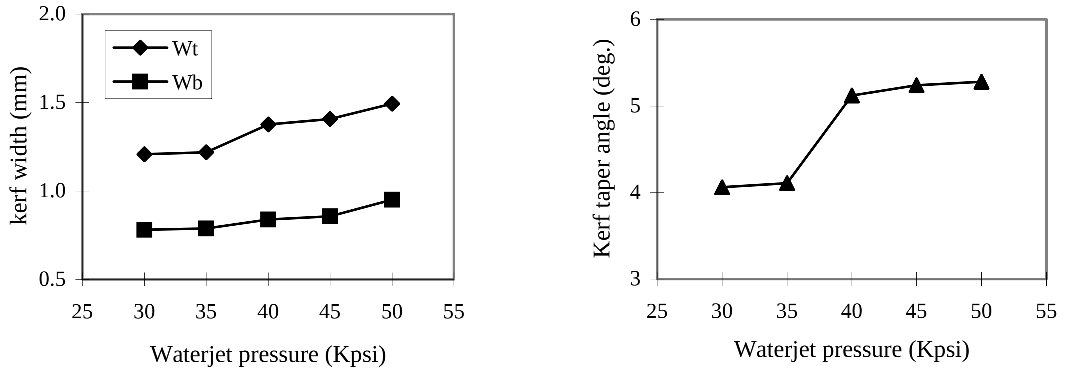


Figure 3. The effect of water pressure on the kerf geometry (traverse speed=1000 mm/min, stand-off distance=4 mm).

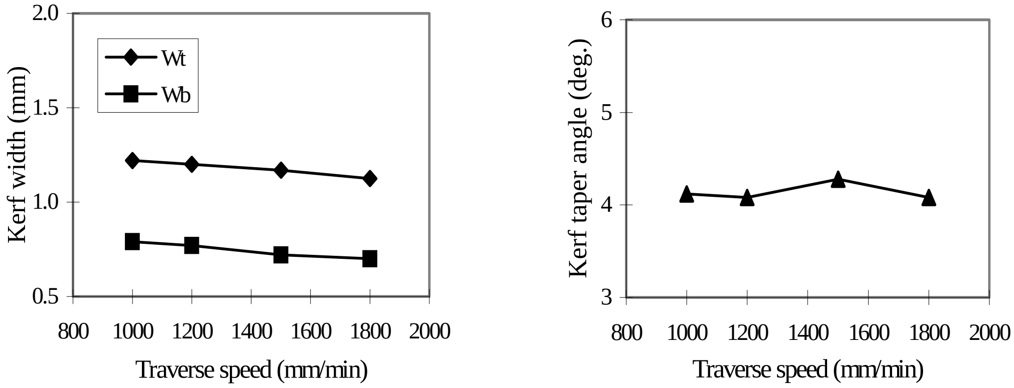


Figure 4. The effect of traverse speed on the kerf geometry (water pressure=35,000 psi, stand-off distance=4 mm).

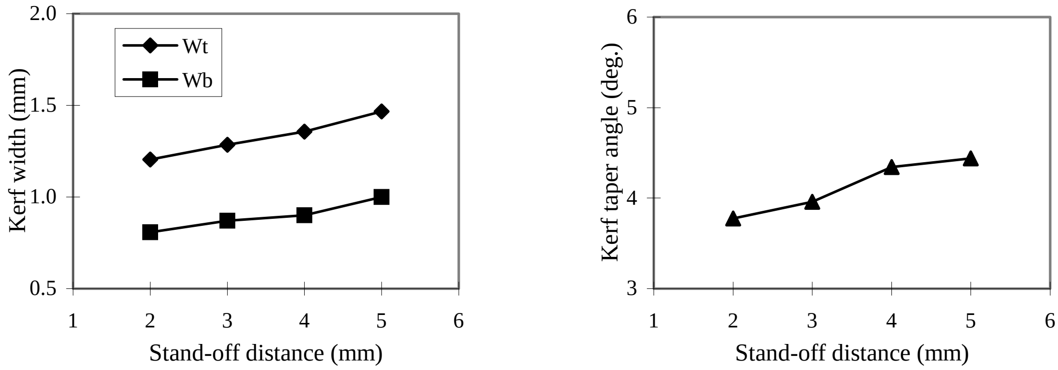


Figure 5. The effect of stand-off distance on the kerf geometry (water pressure=40,000 psi, traverse speed=1500mm/min).

It is interesting to note that the characteristics of the taper angle in terms of water pressure and traverse speed discussed above are opposite to those reported in ceramic cutting [6]. This may stem from the different types of materials processed, different pressure and speed ranges selected as well as different ratios of jet energy used to the energy required to cut the materials.

Figure 5 shows that the top and bottom kerf widths increase with an increase in the stand-off distance although a smaller rate associated with the bottom kerf width is observed. This may be explained as the result of jet divergence when high-velocity waterjets spread out (at different angles) as they exit from the mixing tube. Since the jet is losing its kinetic energy as it penetrates into the work material, the outer rim of the diverged jet will not take effect as it approaches the lower part of the kerf. As such, the stand-off distance has a lesser effect on the bottom kerf width than the top kerf width. As a consequence of this effect, the kerf taper angle is increasing with the stand-off distance, as shown in Figure 5.

It should be noted that if the kerf width and kerf taper can be predicted, they may be compensated in the design and process planning stages and by controlling the nozzle in the machine. For this purpose, a multiple variable regression analysis has been carried out at a confidence interval of 95% which resulted in the following empirical models for the kerf geometry in terms of process variables:

$$W_t = 0.842 + 0.009P + 0.0593S_d - 0.00089V \tag{1}$$

$$\theta = 0.71 + 0.064P + 0.51S_d - 0.000895V \tag{2}$$

where W_t is the top kerf width in mm, θ is the kerf taper angle in degrees, P is the water pressure in 1000psi, S_d is the stand-off distance in mm, and V is the traverse speed in mm/min. The bottom kerf width may be obtained from equations (1) and (2). These equations may be used in practice for kerf geometry estimation as well as for process optimization when the parameters are selected within the domain of the current study.

4.3 Cutting parameter selection consideration

In order to evaluate the overall kerf characteristics and to recommend the optimum combination of the process parameters for cutting the material under consideration, the above analyses and trends are summarised and given in Table 2 where the upwards and downwards arrowheads indicate the increasing and decreasing trends of the quantities, respectively, with an increase in each of the three variables. It appears that an increase in the stand-off distance will result in an increase in the kerf width and kerf taper though the effect on the surface smoothness is not significant. As such, it may be deduced that for the tested material and machine setting conditions, stand-off distance should be selected as small as possible.

Table 2. The effect of cutting parameters on the kerf geometry and quality.

	Stand-off Distance	Traverse Speed	Water Pressure
Top kerf width	↑	↓	↑
Bottom kerf width	↑	↓	↑
Kerf taper	↑	not significant	↑
Roughness/Striation	not significant	↑	↑

Increasing the traverse speed reduces the kerf widths but increases the surface roughness and striation. In addition, traverse speed is directly proportional to the productivity and should be selected as high as possible unless surface roughness is a primary concern. By contrast, an increase in the water pressure will yield increased kerf width, kerf taper and cut surface roughness (and striation). However, higher water pressure will allow higher traverse speed to be used for through cuts. From this study, it is recommended that a water pressure of 30,000 psi with a traverse speed of 1,800 mm/min be used along with a minimum possible stand-off distance.

5. Conclusions

A study of Abrasive Waterjet cutting of polymer matrix composites has been presented based on an experimental investigation. It has been shown that Abrasive Waterjet cutting is a viable and effective alternative for polymer matrix composite processing with good productivity and kerf quality. The analysis and empirical models of kerf characteristics in terms of process parameters have provided a means of estimating kerf geometry and compensating the inclination and width of the kerf in the design and processing stages. The combination of process parameters recommended for the material under consideration may be used for maximizing the productivity while maintaining good kerf quality in practice. The study on the cutting mechanisms and predictive models for the depth of cut in processing thick materials is being carried out and it is hoped to report on this work shortly.

Acknowledgments

The author wishes to thank Mr. J. Gatt at Queensland Manufacturing Institute and Mr. N.R. Sivakumar, a former Masters student of Queensland University of Technology, for their assistance in the experimental work.

References

[1] Krishnan, V.K., “CO_2 laser cutting of polymer matrix composites”, M. Eng. Sc. Thesis, Queensland University of Technology, 1996.

[2] van Luttervelt, C.A., “On the selection of manufacturing methods illustrated by an overview of separation techniques for sheet materials”, Annals of CIRP, 38(2), 1989, pp.587-607.

[3] Hashish, M., “A modeling study of metal cutting with abrasive waterjets”, Journal of Engineering Materials and Technology, 106(1984), pp.221-228.

[4] Matsui, S,. Matsumura, H., Ikemoto, Y., Tsujita, K. and Shimizu, H., “High precision cutting methods for metallic materials by abrasive waterjet”, Proc. 10th International Symposium on Jet Cutting Technology, Cranfield, UK, 1990, pp. 263-278.

[5] Guo, N.S., Louis, G. and Meier, G., “Surface structure and kerf geometry in abrasive waterjet cutting: formation and optimization”, 7th American Waterjet Conference, Seattle, Washington, USA, 1993.

[6] Chen, L., Siores, E. and Wong, W.C.K., “Abrasive waterjet cutting of alumina ceramics”, Proc. 6th International Conference on Manufacturing Engineering, Melbourne, Australia, 1995, pp. 709-713.

[7] Wang, J. and Wong, W.C.K. “Kerf characteristics in abrasive waterjet cutting of metallic coated sheet steels”, Proc. World Congress-Manufacturing Technology Towards 2000, Cairns, Australia, 1997, pp.157-166.

[8] Hashish, M., “A model for abrasive waterjet performance optimization”, Journal of Engineering Materials and Technology, 111(1989), pp.154-162.

[9] Hashish, M., “On the modeling surface waviness produced by abrasive waterjets”, Proc. 11th Int. Symposium on Jet Cutting Technology, Dordrecht, NL, 1992, pp.17-34.

[10] Tan, D.K.M., "A model for the surface finish in abrasive-waterjet cutting", Proc. 8th Int. Symposium on Jet Cutting Technology, Crianfield, UK, 1986, pp.309-313.
[11] Chao, J., Geskin, E.S., and Chung, Y., "Investigation of the dynamics of surface topography formation during abrasive waterjet cutting", Proc. 11th International Symposium on Jet Cutting Technology, Dordrecht, NL, 1992, pp.593-603.
[12] Siores, E. and Wong, W.C.K., Chen, L. and Wager, J.G., "Enhancing abrasive waterjet cutting of ceramics by head oscillation techniques", Annals of CIRP, 45(1), 1996, pp.215-218.
[13] Koenig, W., "Machining of fibre reinforced plastics", Annals of CIRP, 34(2), 1985, pp.537-548.
[14] Chen, L., Siores, E. and Wong, W.C.K., "High-pressure abrasive waterjet erosion process", Proc. Pacific Conference on Manufacturing, Seoul, Korea, 1996, pp.642-647.