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Study of Cutting Fiber-Reinforced Composites by Using Abrasive Water-Jet with Cutting Head Oscillation

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Abstract

An experimental and theoretical research work on abrasive waterjet (AWJ) oscillation cutting of Glass Fiber Reinforced Polymer (GFRP) composite materials was conducted at the Water-jet Laboratory of the Industrial Research Institute of Swinburne (IRIS). The objective of this research work was to conduct a comparative study of the oscillation and normal (without head oscillation) cutting of GFRP composite materials and compare the performances the two processes. This new technique which is a variant of the traditional AWJ cutting technique, makes use of a back and forth motion of the cutting head which is superimposed on the normal linear motion to effect optimum loading of the cutting forces on the workpiece material and scan the cut-wall surface to also improve surface finish. The technique was used for cutting GFRP composites materials and the qualities of resulting surfaces were measured using stylus type equipment. A comparison of the results indicates that there is significant improvement in the quality of surfaces produced by head oscillation technique than normal AWJ cutting. In some of the samples, an improvement, in surface quality, as measured by Ra values, up to 20 percent was found.

1 Introduction

Glass fibre reinforced polymer (GFRP) composites are increasingly being used in a large number of applications because of the superior advantages they offer compared to other traditional and non-traditional materials. The advantages GFRPs offer compared to other materials are well documented and include high strength to weight ratio, high modulus, high fracture toughness, and corrosion and thermal resistance. In addition to these advantages, the relative ease of manufacture of components using GFRPs, thus low cost of production, makes these materials candidates for more and more applications.

Currently the applications to which GFRPs have been put to use include automotive and aircraft components, boat hulls, building panels, household and industrial appliances. In production of components using GFRPs and other composites, the items are often made in a net shape or close to a net shape. Although this reduces machining to a minimum in most cases, the need for machining operations after forming the basic shapes of components to be used for applications that require a high degree of finish remains. In addition, for some applications it might be more economical to produce components by machining from blank composite panels or rods having the required properties.

A number of tools and associated techniques are used in industry for performing post-forming operations including the traditional machining techniques and tools, which sometimes partially modified and used for these purposes. The non-traditional machining techniques used for machining composites include laser, abrasive waterjet, electrical discharge machining, ultrasonic assisted machining and electrochemical spark machining. However, regardless of the tools and techniques used, machining composites present a special challenge for both traditional and non-traditional techniques because of the inhomogeneity and anisotropy of these materials.

The main difficulty encountered when machining composites using traditional techniques and some non-traditional techniques such as laser cutting is the high heat dissipation into the workpiece material that can cause charring, thermal cracks and other surface and subsurface defects on these components. The other problems associated with these machining techniques include delamination and fiber pull out from the composites material, and the rapid wear of the tools used in conventional machining due to the hard and abrasive fibers in these composites. Therefore, it is usually necessary to use wear resistant and expensive cutting tools such as coated or un-coated cemented carbide, cubic boron nitride (cBN) and diamond impregnated tools for machining these materials using conventional machining. Machining GFRPs and some of the other composite materials using traditional machining techniques and tools such as mills and lathes might also result in excessive dust being generated around these machines that can be harmful to operators if inhaled.

Abrasive waterjet (AWJ) cutting is a non-traditional machining techniques that overcomes most of the problems associated with traditional machining and some non-traditional machining technique such as laser cutting. Laser cutting involves the dissipation of heat into workpiece material that makes the process unsuitable for composites such GFRPs. However, in some cases the effect can be reduced with appropriate use of the laser source and material combinations [1].

AWJ cutting technique is well suited for processing composite materials because of reduced interface temperature, low mechanical loading, better surface integrity and ease of operation. However, although this cutting technique overcome the difficulties associated with cutting composites using other traditional and non-traditional techniques, it itself suffers from the formation of striations or wavy patterns of varying depth along the cut-wall surface of products as shown in Fig. 1. The characteristic feature of the cut-wall surface topography of relatively thick materials constitutes a distinctly smooth upper zone and a striated or wavy lower zone [2,3] as shown in Fig. 1(a). In addition to these waviness or striations in the lower zone, the material surfaces also exhibit roughness of a random nature superimposed on these wavy patterns as shown in Fig. 1(b). In cutting composites using abrasive waterjet the highly directional loading of the abrasive particles on the workpiece material, which is a characteristics of the cutting process, might also be possible source of observed defects such as fibre delamination and fiber pull out.

The cutting head or nozzle oscillation technique, which was introduced by Veltrup [4] and successfully used in AWJ cutting by Siores et al. [5] and Chen et al. [6], has been found to be an effective way in increasing the performance of AWJ cutting for cutting

metallic materials. In this technique, the cutting head is moved in an angular direction parallel to the cutting direction (in the cutting plane) at a given angle and frequency of oscillation. This paper presents an experimental investigation on the effect of using this nozzle oscillation technique in the AWJ cutting of GFRP composite materials and a quantitative evaluation of the improvement in the depth of the smooth cutting zone and the reduction of the striations from the rest of the machined surfaces of GFRP composites as a result of the oscillation.

2 Literature Review

The widely accepted explanation for the physics of the material removal process and the striation formation mechanisms for ductile and homogenous materials is that of Hashish [3,7] who conducted an investigation of the AWJ cutting process using a high-speed camera to record the material removal process in a plexiglass sample. He found that the material removal process is a cyclic penetration process that consists of two cutting regimes, which he termed “cutting wear zone” and “deformation wear zone” following Bittar’s erosive theory [8,9]. The two zones of cutting and the abrasive particle trajectory path in these zones are shown in Fig. 2.

Hashish also proposed that the cutting process consists of three stages, which are the entry stage, the cyclic cutting stage and the exit stage as shown in Fig. 3. In the cutting wear zone, material removal is by abrasive particles striking the workpiece at shallow angles of attack while material removal in the deformation wear zone is by the abrasive particles impinging at large angles of attack. The general erosion process proceeds in a cyclic manner with steady material removal up to a critical depth h_c followed by the formation and removal of steps as the cutting depth increases. Below this critical depth h_c , the material removal process is unsteady, resulting in the formation of striations or waviness on the wall of the cut surface [10]. Thus the change of material removal process from one mode to another is suggested to be the cause of striation or waviness [3].

The material removal process in ductile materials is regarded to be mainly due to erosion at shallow angles and plastic deformation at large angles [7]. However, in contrast, the material removal process in brittle materials is viewed as brittle fracture process i.e. material removal occurs by mainly chipping [11]. El-Domiaty and Abdel-Rahman [11] proposed elastic-plastic erosion models based on fracture mechanics for determining the maximum depth of cut and surface finish. However, the authors found that it is more crucial to view the material removal process based on the assumption that plastic deformation plays an important role. The models were constructed to predict the maximum depth as a function of the fracture toughness, hardness and process parameters. Erosion or chipping process of brittle materials is controlled by the formation of cracks and their propagation. The fracture toughness of the material, a measure of the materials resistance to crack propagation, is used in the models [11].

GFRPs, like most other composites, are inhomogeneous materials that contain both ductile and brittle behaving materials, which interact differently with the forces exerted by the incoming abrasive jets [1]. König et al. [12] who experimentally investigated waterjet cutting of fiber reinforced plastics report that the variation of measured roughness values are significantly higher than that of metals because of the inhomogeneous nature of

these materials. Ramulu and Arola [13] propose that the material removal mechanism in composite cutting is a combination of shearing, micro machining and erosion. Wang [14] who experimentally investigated the cutting process of polymer matrix composites using AWJ propose a semi-empirical model for the depth of cut. This model, which was developed using the energy approach, is in good agreement with the experimental results[14].

Striation formation mechanisms in homogenous materials have been investigated by a number of researchers who have proposed various models of differing accuracy to describe this phenomenon associated with the abrasive waterjet cutting processes. Among the various techniques developed to increase the performance of AWJ cutting, such as multipass cutting [15], angling the jet forward in the cutting plane [5,14] and cutting head oscillation [6,14], the cutting head oscillation technique has been found to be the most effective way that can result in a reduction in striations and improve the quality of surface finish of metallic materials without significantly compromising its competitive advantages. The work in this paper is to study qualitatively the effect of cutting head oscillation on the performance of AWJ cutting on composites which are inhomogeneous materials.

3 Experimental Setup and Procedure

The experimental set up used for the experiments consisted of a high pressure intensifier pump and a 6-degrees of freedom robot fitted with the high pressure waterjet accessories, a receiver and an abrasive feeding and mass flow monitoring system. The intensifier was capable of supplying water up to a maximum pressure of 55,000 psi (380 Mpa), while the robot was to position and move the nozzle to carry out the cutting.

A number of factorial experiments in which the oscillation angle, frequency of oscillation, waterjet pressure, mass flow rate and the nozzle traverse speed was varied within practical ranges were designed and carried out. In these experiments, the oscillation angle was varied from two degrees to six degrees while the oscillation frequency was varied from 60 to 360 cycles per minute or one to six cycles per second. The traverse speeds used for processing the unidirectional GFRP composite with thickness 10mm were in the range from 120 to 300 mm per minute. In addition, factorial experiments for normal cutting (without oscillation) at the same mass flow rate, traverse speed, and waterjet pressure was designed and performed.

For oscillation cutting experiments, the robot was programmed to simultaneously execute the linear motion (the traverse speed) and the oscillation motion of the cutting head in a given sequence. The oscillation movement consisted of a forward angular movement at a given angle and angular speed and a backward or return movement to the original position of the arm with the same speed. The original position of the nozzle is perpendicular to the workpiece surface.

The other parameters used were:

- Nozzle diameter: 1.33 mm
- Stand off distance: 2 mm

The R_a values for each of the surfaces were measured using stylus type equipment at three points from the top edge of the cut-wall. The sampling length used for measuring the R_a values at these preselected points was 12 mm with a cut-off of 0.8 mm.

5 Results and Discussion

The experimental results for the GFRP composites processed at traverse speeds of 120 and 300 mm/min. are shown in Fig. 4 for normal (with no oscillation) and oscillation cutting. The frequencies of oscillation used with these traverse speeds were 2 and 6 cycles per second while the angle of oscillation was 2 and 6 degrees. These levels of oscillation angle and frequency of oscillation were combined in various ways to investigate the effects of the different levels on the surface finish. The results show that the surface qualities for materials processed using the head oscillation technique were significantly better than that of surfaces produced by the traditional or normal AWJ cutting technique for most of the combinations of the levels of oscillation angle and frequency of oscillations.

Fig. 4 (a) shows the highest improvement in surface quality that was found in samples processed with both high levels of the oscillation angle and frequency of oscillation. At the lower traverse speed of 120 mm/min. and frequency of oscillation and oscillation angle of 6 Hz and 6 degrees respectively, the average value of R_a for the samples cut with head oscillation was about 20 percent lower than that using the normal AWJ technology. The worst result was found for materials processed at a frequency of oscillation of 6 Hz and angle of oscillation of 2 degrees while various degrees of improvement were obtained in other combinations of the oscillation angles and frequencies.

The increase in traverse speed from 120 to 300 mm/min. results in increase in all values of the surface measurement as will be expected and is shown in Fig. 4 (b). Although, these changes in the measured surface roughness values were somewhat uniform, however, in some cases, the changes were accompanied by change in the profile of the roughness measured as the distance from the top edge increases. In addition, the improvements in surface quality, found by processing using head oscillation technique, at these higher traverse speeds were consistent across all combinations of the angle and oscillation frequency except at oscillation frequency of 6 Hz and angle of oscillation of 2 degrees.

The effect of an increase in abrasive mass flow rate from 0.23 Kg/min. to 0.32 kg/min. are shown in Fig. 5. The result shows that there is a consistent improvement in surface quality with most of the samples processed with oscillation technique compared to normal cutting. However, unlike in the case of the lower mass flow rate of 0.23 Kg/min., the worst result for surface improvement was found in case of the oscillation angle and frequency of oscillation of 2 degrees and 2 Hz respectively in both cutting speeds at these higher mass flow rates. However, in the higher cutting speed of 300mm/min., all the samples show improvement in quality except close to the top edge of the cut-wall surface. This indicates that in addition to the oscillations parameters, frequency and angle, and the cutting speed, the surface improvements are influenced by the abrasive mass flow rate.

The results of the experiments conducted to investigate the effect of increasing pressure on the surface finish are plotted in Fig. 6 for traverse speeds of 120 and 300 mm/minute. These results show that while there is a continued improvement in quality of surfaces processed with oscillation technique compared to normal cutting (without oscillation), the

changes were not significant when compared to samples processed at the lower pressure of 172.4 Mpa. In addition, the improvements in surface qualities were more mixed i.e. depend on the distance from the top edge of the cut-wall, in the case of the lower cutting speed of 120 mm/minute. However, these improvements were more consistent through out the cut-wall thickness and across all oscillation parameters, frequency and angle, used to process the samples in the case of the higher cutting speed of 300mm/minute.

Experiments were also conducted at the same pressure by increasing the mass flow rate from 0.23 to 32 kg/min. to investigate its effect on the quality of surface finish. The results of the experiments that are plotted in Fig. 7 show a similar trend as that observed in the case of the lower pressure of 172.4 Mpa shown in Fig. 5. As in that case, the results here show an improvement in surface quality when mass flow rate was increased at lower cutting speed of 120 mm/min., and mixed results when the cutting speed is further increased to 300 mm/min.

The experimental results at intermediate values for pressure, cutting speed, mass flow rate, and oscillation parameters, frequency and angle of oscillation, plotted in Fig. 8 show a clear improvement in surface quality of products processed using oscillation cutting technique than normal (without oscillation).

A regression analysis was applied on the experimental data obtained for both normal and oscillation cutting to gauge the effects of the operating parameters used in these processes. The results of these analyses that in addition to the operating parameters, mass flow rate, waterjet pressure, oscillation frequency, angle of oscillation and the traverse speeds, which also included the change of Ra values with the distance from the top edge of the cut-wall surface, were of the following form:

$$R_a = 6.205 - 0.0004p - 14.470\mu + 0.346S + 0.158d$$

for normal cutting and

$$R_a = 4.683 - 0.004p - 5.168\mu + 0.003S - 0.024d - 0.092\xi - 0.102\alpha$$

for oscillation cutting. Adjusted R-squared values were 80.8 and 87.5 percent for normal and oscillation cutting respectively with a confidence interval of 95 percent.

Where p is the waterjet pressure in Mpa, μ the mass flow rate in Kg/min., S the traverse speed in mm/min., d is the distance from the top edge of the cut-wall surface in mm, ξ and α are the oscillation frequency in Hz and the angle of oscillations in degrees respectively.

The regression analysis for both oscillation cutting and normal cutting (without oscillation) above and the box plot of the data shown in Fig. 9 show very little dependence of the surface finish on the waterjet pressure used in the experiments. However, this is not supported by other results in the literature [2,3] that show improvement in surface quality with an increase in waterjet pressure. The reason for this discrepancy might be due to the relatively narrow range of pressure, 172.4 to 241.3 Mpa, which was used in the experiments conducted.

Although not very significant, the box plot of the experimental data in Fig. 9 (b) shows that there is some improvements of the surface finish quality with an increase in waterjet pressure for samples cut with the normal AWJ technique. However, as the Figure show, there was no change in the mean value of R_a measured for surfaces produced using both cutting techniques as the waterjet pressure increases from 172.4 to 206.9 Mpa. In addition, there was a large spread about the mean of the measured R_a data for samples processed at 172.4 and 241.3 Mpa. Despite this, comparing Fig. 9 (a) and (b) it can be seen that in general surfaces produced by the head oscillation technique have a better surface quality than those produced by normal cutting i.e. without superimposing the nozzle head oscillation.

The trend observed for change in oscillation frequency and oscillation angle is shown in Fig. 10 (a) and (b) for all the oscillation cutting experiments. This box plot shows that the better quality of surface is obtained with samples processed with higher oscillation angle and frequency. However, the improvements in surface quality with increase in the angle of oscillation is much higher than that observed with an increase in the oscillation frequency as shown in the figure. There is, however, a large spread of the data about the mean, which is due to changes in other operating parameters such as waterjet pressure and mass flow rate.

6 Conclusion

The results obtained indicate that improvements in surface quality as measured by R_a values can be achieved by using oscillation cutting of GFRP composites. The results also indicate that:

- The improvements in surface quality are better when high values of the frequency of oscillation and angle of oscillation are used
- The improvements in surface quality are much higher with increase in the angle of oscillation than with increase in the frequency of oscillation
- The lowest improvement in surface quality was obtained when high value of frequency and a low value of the angle of oscillation was used

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Fig. 1. Typical appearances of the smooth upper zone and the striated and rough zone [3].

Fig. 2. The wear cutting and deformation cutting mode parameters proposed by Hashish [7].

Fig. 3. The three stages in the cutting process, the entry stage, the cyclic cutting or developed kerfing stage and the exit stage[7].

(a)

(b)

Fig. 4. Oscillation and traditional cutting results: (a) traverse speed = 120 mm/min., (b) traverse speed = 300 mm/min. Abrasive mass flow rate = 0.23 Kg/min and waterjet pressure = 172.4 Mpa for both cutting speeds.

Fig. 5. Oscillation and traditional cutting results: (a) traverse speed = 120 mm/min., (b) traverse speed = 300 mm/min. Abrasive mass flow rate = 0.32 Kg/min and waterjet pressure = 172.4 Mpa for both cutting speeds.

Fig. 6. Oscillation and traditional cutting results: (a) traverse speed = 120 mm/min., (b) traverse speed = 300 mm/min. Abrasive mass flow rate = 0.23 Kg/min and waterjet pressure = 241.3 Mpa for both cutting speeds.

Fig. 7. Oscillation and traditional cutting results: (a) traverse speed = 120 mm/min., (b) traverse speed = 300 mm/min. Abrasive mass flow rate = 0.32 Kg/min and waterjet pressure = 241.3 Mpa for both cutting speeds.

Fig. 8. Oscillation and traditional cutting results at a traverse speed = 210 mm/min., and abrasive mass flow rate = 0.27 Kg/min and waterjet pressure = 206.9 Mpa.

Fig. 9. Box plot R_a vs. waterjet pressure for (a) oscillation and (b) normal cutting for all the parameters used in the experiments.

Fig. 10. Box plot R_a vs. oscillation frequency and oscillation angle for all the parameters used in the oscillation experiments.