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INVESTIGATION ON ABRASIVE WATERJET MACHINING OF KEVLAR REINFORCED PHENOLIC COMPOSITE USING TAGUCHI APPROACH

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ABSTRACT

Experimental investigations were conducted to assess the influence of Abrasive Water Jet Machining (AWJM) process parameters on surface roughness (R_a) and kerf taper ratio (T_R) of aramid fibre reinforced plastics (AFRP) composite. The approach was based on Taguchi's Method and Analysis of Variance (ANOVA) to optimize the AWJM process parameters for effective machining. It was found that traverse rate was considered to be the most significant factor followed by hydraulic pressure in influencing the R_a quality criteria. In case of T_R, traverse rate showed the greatest influence by standoff distance. The recommended optimal parametric combination for improved R_a and T_R performance are A3B2C3D1 and A3B3C3D1 respectively. It was also confirmed that increasing the kinetic energy of water jet may produce a better quality of cuts. It was confirmed that determined optimal combination of AWJM parameters satisfy the real need for machining of AFRP composites in practice.

Keywords: AWJM, AFRP, Taguchi's Method, Piecewise Linear Regression.

1. INTRODUCTION

Abrasive water jet machining (AWJM) process is one of the non-traditional machining processes that have been used extensively in various industry related applications. The basic principles of abrasive water jet machining (AWJM) were reviewed in details by [1]. This technology is less sensitive to material properties as it does not cause chatter, has no thermal effects, impose minimal stresses on the workpiece, and has high machining versatility and high flexibility. But it has some drawbacks; especially it may generate loud noise and a messy working environment [2, 3].

The use of composite materials becomes prominent in today's modern technological applications. These materials have better mechanical properties such as low densities, high strength, stiffness and abrasion, impact and corrosion resistances. The creation of aramid fibres called Kevlar has lead to the big breakthrough in the development of modern ballistic armour due to its unique properties of special application in armour which give ballistic protection [4]. It has unique characteristics such as high strength to weight ratio, high chemical resistance, high cut resistance, flame resistance and good corrosive resistance [4].

Machining of AFRP composites requires the need for better understanding of cutting processes regarding accuracy and efficiency. Moreover, due to the anisotropic and non homogeneous nature of composites, their machining behaviour differs in many aspects from metal machining. In conventional machining processes notably drilling is the most frequently employed machining operation of composite materials. Drilling of composite laminates causes more wear of the drill compared to drilling on conventional materials mainly due to heterogeneity of the work material which leads the drill bit to experience variable forces resulting in damage of work material such as delamination, fibre pull out and poor hole quality [5]. Due to these limitations of conventional machining processes, alternative techniques that utilize non-conventional energy sources for material removal such as electrical discharge machining (EDM), laser cutting, ultrasonic machining, waterjet and abrasive waterjet machining has drawn much interest and has been studied the feasibility of the processes [6]. Among these non-conventional machining processes, abrasive waterjet machining is the only method used in industry today for trimming fibre reinforced composite materials as laser machining suffers from the problem of a large heat-affected zone, while EDM suffers from extremely low cutting rates [7].

The AWJM process provides a single tool that is suitable for machining a wide range of composite materials. It is a non-contact, inertia-less and faster cutting process that offers some advantages like narrow kerf width, negligible heat affected zone, reduced waste materials and flexibility to machining process in different ways [8]. In the AWJM process, the possibilities of environmental contamination due to fibrous materials are significantly reduced or eliminated since water jet washes away the eroded material from the surface of the workpiece [9].

There are numerous associated parameters and factors of AWJM process that can influence the surface quality of the AWJ machined surfaces [8, 10]. However, in the present study only four three-level factors were considered for analysis. In the present study, the effect and optimization of machining parameters in terms of surface roughness and kerf taper ratio will be investigated using Taguchi method and ANOVA. The empirical model for the prediction of surface finish in terms of machining parameters will be established by means of piecewise linear regression analysis.

2. EXPERIMENTAL WORK

2.1 Material

In present study, Kevlar 129 was used and hand laminated in the prepreg form of modified phenolic resin having its real weight of 410 g/m^2. The aramid fibres which was readily available in a woven fabric and named for its manufacture's style of 258 (2x2 basket weave) were used for the preparation of the laminates. The fibre fabrics were cut into squares of 300 mm x 300 mm. The layers were properly stacked into 22 plies. The laminates were cured at a pressure of approximately 80 kg/cm^2 in a 100 tons Wabash hot press. The actual thickness of the laminate was 9.2 mm. The orientation of fibre within the fabric was kept constant all the time during lay-up process hence they are considered as bidirectional laminates [0°/90°]. The fibre filament has a diameter of 12 µm. The mechanical properties of Kevlar 129 are given in Table 1.

Table 1: Mechanical properties of Kevlar 129 [11]

Density (g/cm^3)	Ultimate Tensile Strength (GPa)	Tensile Elongation (%)	Tensile Modulus (GPa)	Max, Use Temp. (°C)
1.45	3.4	3.3	99	250

2.2 Equipment

The equipment used for machining the samples was Excel-CNC abrasive waterjet cutting machine equipped with Ingersold Rand model of water jet pump with the designed pressure of 345 MPa (50,000 psi). The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve and a workpiece table with dimension of 1200 mm x 2400 mm. For the nozzle assembly, it has an orifice of 0.25 mm diameter of sapphire jewel and a focusing tube of 0.76 mm internal diameter of carbide with a focus length of 70 mm. Throughout the experiments, the nozzle was frequently checked and replaced with a new one if the nozzle was worn out significantly. All experiments were conducted using garnet as the abrasive with mesh size of #80 (≈ 177 µm). This size was selected due to its most applications in industrial operations of abrasive water jet machining.

2.3 Experimental Design

In the present study, four machining parameters were selected as control factors as shown in Table 2. The parameters and levels were selected primarily based on the literature review of some studies that had been documented on AWJ machining on graphite/epoxy laminates [12], Kevlar composite [13], ceramic materials [14], structural metal alloys [15], metallic coated sheet steels [16] and fibre-reinforced plastics [17, 18]. Based on Taguchi's method DOE, an L_{81} (3^{40}) orthogonal arrays table with 81 rows (corresponding to the number of experiments) was selected for the experimentation [19, 20]. In the present study only involved four machining parameters, therefore the remaining columns in the L_{81} orthogonal array were kept unused.

Table 2: Machining parameters and their levels

Machining Parameters	**Symbols**	**Level**		
		1	**2**	**3**
Pressure (MPa)	A	172	241	310
Abrasive-mass flow rate (g/s)	B	5.0	7.5	10.0
Standoff distance (mm)	C	4.0	3.0	2.0
Traverse rate (mm/s)	D	0.5	1.5	3.0

For each experimental run, the machining parameters were set to the pre-defined levels according to the orthogonal array. Squares of 20 mm × 20 mm of the test specimens were cut out with full penetration as shown in Figure 1. All machining procedures were done using a single-pass cutting. Some of the machining parameters were kept constant during the experiments. These parameters are water-orifice diameter of the nozzle (0.01 inch ≈ 0.254 mm), impact angle (90º), focusing diameter of the nozzle (0.03 inch ≈ 0.762 mm) and focusing length of the nozzle (2.75 inch ≈ 69.85 mm).

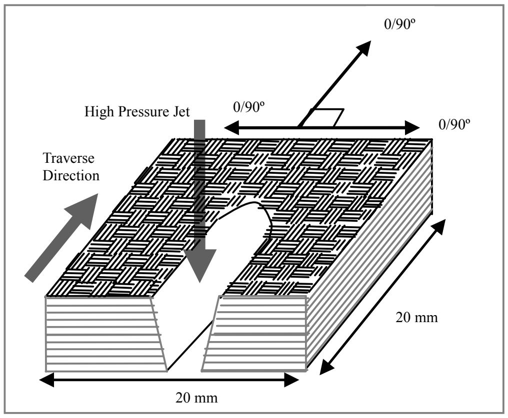

Fig 1: Illustration of AWJ cutting on Kevlar laminate

A surface roughness measuring device, SURFPAK SV-514, equipped with a cone-shaped diamond stylus having the diameter of 10 µm and tip angle of 90º was used in this study. The measurement of surface roughness of each specimen was obtained at the middle of depths cut (4.6 mm depth). Due to the variability of surface finish data, multiple measurements were taken of each surface evaluated so that averages could be calculated. All measurements were acquired using 0.8 mm cut-off length.

3. RESULTS AND DISCUSSION

3.1 Effect of Machining Parameters

The effect of control factors were investigated through the analysis of variance (ANOVA). It is a computational technique conducted mainly to learn about the influence of various design factors and to observe the degree of sensitivity of the result to different factors affecting the quality characteristics. *F*-ratio value is a statistical analogue to Taguchi's signal to noise ratio for the control factor effect versus the experimental error [19, 20]. It uses the information based on sample variances to define the relationship between the power of the control factor effects and the power of the experimental error. Larger *F*-ratio value indicates that there is a big change on the performance characteristic due to the variation of the process parameter.

Table 3: ANOVA and *F*-ratio for R_a

MP	**DOF**	**SS**	**V**	***F***	**P**
1. A	2	19.22	9.61	6.97	6.86
2. B	(2)	(1.10)	- Pooled (CL ≈ 0 %) -		
3. C	(2)	(3.35)	- Pooled (CL = 70.28%) -		
4. D	2	156.26	78.13	56.68	55.76
Error	72	104.76	1.38	-	37.31
Total	81	280.24	-	-	100.00

Table 4: ANOVA and *F*-ratio for T_R

MP	**DOF**	**SS**	**V**	***F***	**P**
1. A	(2)	(56.04)	- Pooled (CL = 94.59%) -		
2. B	(2)	(46.66)	- Pooled (CL = 96.21%) -		
3. C	(2)	89.44	44.72	6.16	7.95
4. D	2	483.10	241.55	33.27	42.97
Error	72	551.83	7.26	-	49.08
Total	81	1124.37	-	-	100.00

MP – Machining Parameters, DOF – Degree of Freedom, SS – Sum of Squares, V – Variance, *F* – F-ratio, P – Percentage of Contribution, CL – confidence level

Table 3 shows the ANOVA and *F*-ratio values on machining performance of R_a. This analysis was carried out for a 99.5% confidence level. It was found that factor B (abrasive mass flow rate) and C (standoff distance) failed the test of significance at 99.5% confidence level and therefore, they were pooled [19, 20]. The factors that pass the test of significance are considered significant. They are considered insignificant if they fail the test of significance and are usually treated as if they are not present. This process is called pooling. Control factor D which is the traverse rate is the most significant factor influencing the assessment of R_a followed by control factor A (hydraulic pressure). Control factors B (abrasive mass flow rate) and C (standoff distance) are insignificant in influencing R_a since they failed the test of significance.

In case of T_R as shown in Table 4, it was found that factor A (hydraulic pressure) and B (abrasive mass flow rate) failed the test of significance at 99.5% confidence level. Therefore they are considered as not significant in influencing the T_R characteristic. Control factor D (traverse rate) is the most significant factor influencing the assessment of T_R followed by control factor C (abrasive mass flow rate).

The optimum condition represents the combination of control factor levels that is expected to produce the best performance. The average S/N ratio for each factor level indicates the relative effects of the various factors on quality characteristic of R_a during machining of kevlar/phenolics composites. Taguchi Analysis observes the higher value of mean S/N ratio as better quality characteristic. Therefore, based on the average S/N ratio for each factor level as illustrated in Based on Figure 2 and 3, the optimum machining performance for both R_a and T_R was obtained at level 3 for hydraulic pressure (310 MPa), level 3 for abrasive mass flow rate (10 g/s), level 3 for standoff distance (2 mm) and level 1 for traverse rate (0.5 mm/s). The optimum parametric combination for both R_a and T_R is A3B3C3D1.

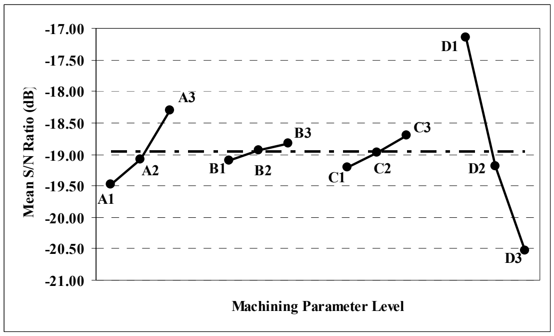

Fig 2: Average S/N ratio by control factor level for R_a

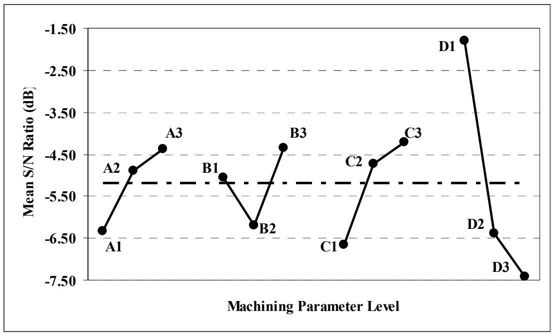

Fig 3: Average S/N ratio by control factor level for T_R

In AWJM process, increasing the kinetic energy of the jet may result in better penetration capability. It is shown that at optimum condition, the levels of machining parameters found are intended to produce the highest amount of kinetic energy of the water jet. In case of hydraulic pressure, a higher hydraulic pressure increases the kinetic energy of the abrasive particles and enhances their ability for material removal. As a result the surface roughness decreases [9, 15]. In case of abrasive flow rate, the higher the abrasive flow rate, the higher the number of particles involved in the mixing and cutting processes [1, 15]. An increase in abrasive flow rate leads to a proportional increase in the depth of cut. When the abrasive flow rate is increased, the jet can cut through the laminate easily and as a result, the cut surface becomes smoother.

In case of standoff distance, generally, higher standoff distance allows the jet to expand before impingement which may increase vulnerability to external drag from the surrounding environment [1, 9]. Therefore, increase in the standoff distance results an increased jet diameter as cutting is initiated and in turn, reduces the kinetic energy density of the jet at impingement. It is desirable to have a lower standoff distance which may produce a smoother surface due to increased kinetic energy. In case of traverse rate, it can be anticipated as increasing the traverse rate allows less overlap machining action and fewer abrasive particles to impinge the surface, increasing the roughness of the surface [8, 9, 18]. In this case, a lower traverse rate is desirable to produce a better surface finish as proven from the S/N ratio analysis as shown in Figure 2 where the optimum condition for traverse rate is at level 1 which is the slowest traverse rate.

Kerf geometry is a significant characteristic in abrasive waterjet machining. Generally after a through cut using abrasive waterjet a tapered slot will be produced with the top being wider than the bottom. According to [1], a general trend of AWJM parameters shows that the taper increases with an increase in the traverse rate and the standoff distance while it decreases with an increase in the pump pressure. These results suggest that the taper reduces with an increase in the abrasive water jet kinetic energy and in general it agrees with the present study.

As expected that higher hydraulic pressure should result in greater jet kinetic energy and open a wider slot on the workpiece on both of the top and bottom widths. As a consequence, the kerf taper ratio is calculated as the ratio of top to the bottom width is reduced with further increase of supply hydraulic pressure due to the more rapidly increasing of top kerf width compared to the bottom kerf width. This trend for kerf taper ratio is similar to the surface roughness and it can be explained and supported by the strength zones in a water jet proposed by [8] and further developed by [16]. With the increase of water pressure, the effective jet width or the diameter of the jet increases. This causes the overlapping of a larger effective jet produces a wider kerf as well as a smoother surface than a smaller jet.

The kerf taper ratio increases with the increase in standoff distance. As explained by [12], higher standoff distance allows the jet to expand before impingement and lowers the densities of abrasive particles in the outer perimeter of the expanding jet. This generally results in lower penetration depth as well as a higher surface roughness. Thus, increasing the standoff distance between the nozzle and workpiece is expected to result higher difference of top and bottom kerf widths which eventually gives higher taper ratio as it is calculated as the ratio of top to the bottom width. Moreover, the result is also believed to be caused by the jet divergence [13]. As the jet penetrates into the glass fibre laminate, it loses its kinetic energy and consequently the outer rim of the diverged jet does not take its effect as it approaches the lower part of the kerf.

As explained by [1], the higher the abrasive flow rate, the higher the number of particles involved in the mixing and cutting processes. Every increase in the abrasive flow rate leads to a proportional increase in the depth of cut. Therefore, the jet will have higher kinetic energy and consequently will gain higher ability to penetrate the workpiece. As a result, there will be a relatively wider width for both top and bottom kerf widths and giving a smaller ratio of kerf taper.

Actually, the effect of traverse rate on the kerf taper was also found to be similar to that observed on the surface roughness. It is concluded that the negative effect of traverse rate on the kerf width is due to the fact that a faster passing of abrasive water jet allows fewer particles to strike on the target material and, hence, generates a narrower slot [16]. In other words, the decrease in the exposure time that was caused by increasing the traverse rate resulted to the reduction in both of the kerf top and bottom width. Whereas, the increasing trend of the kerf taper ratio is the result of the more rapidly decreasing kerf width at the bottom than at the top as the traverse rate increases.

Table 4: Result of the confirmation experiment, R_a

	Initial cutting parameters	Optimal cutting parameters	
		Predicted	Experimental
Setting level	A2B2C2D2	A3B2C3D1	
R_a (µm)	11.3		5.68
S/N Ratio	-21.062	-16.506	-15.097

Table 5: Result of the confirmation experiment, T_R

	Initial cutting parameters	Optimal cutting parameters	
		Predicted	Experimental
Setting level	A2B2C2D2	A3B3C3D1	
T_R (mm/mm)	3.82		2.79
S/N Ratio	-9.005	-5.203	-5.033

3.2 Confirmation Test

The confirmation tests were conducted using the optimum combinations of machining factors. These confirmation tests were used to predict and verify the improvement in the quality characteristics for machining of kevlar/phenolics composites with respect to the chosen initial parameter setting. Table 4 and 5 show the comparison of the predicted and actual machining performance for R_a and T_R respectively using their respective optimum cutting parameters. The improvements of S/N ratio with respect to the initial parameter setting are 5.965 dB and 3.972 dB respectively for R_a and T_R. It is also shown in the same tables that the predicted S/N ratios for both criteria are comparable to the experimental ones.

4. CONCLUSIONS

On the basis of experimental results, calculation of S/N ratios (dB), analysis of variance (ANOVA), F-test values, confirmation test results and development of mathematical models, the following conclusions can be drawn for effective machining of Kevlar/phenolics composite by AWJM process as follows:

1. The traverse rate is the most significant control factor on surface roughness during AWJM followed by hydraulic pressure. Meanwhile, standoff distance and abrasive mass flow rate are insignificant in influencing R_a since they failed the test of significance. The recommended parametric combination for optimum surface finish is A3B3C3D1.
2. In case of T_R, traverse rate is the most significant control factor followed by standoff distance. Hydraulic pressure and abrasive mass flow rate are considered insignificant in controlling T_R criteria. The recommended parametric combination for optimum kerf taper ratio is A3B3C3D1.
3. It was also confirmed that increasing the kinetic energy of water jet may produce a better quality of cuts.
4. The experimental result for the optimal setting shows that there is considerable improvement in the process.

5. NOMENCLATURE

Symbol	Meaning	Unit
A	Hydraulic pressure	(MPa)
B	Abrasive mass flow rate	(g/s)
C	Standoff distance	(mm)
D	Traverse rate	(mm/s)
R_a	Surface roughness	(µm)
T_R	Kerf taper ratio	(mm/mm)
S/N	Signal to noise ratio	(dB)

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