INFLUENCE OF AWJM PARAMETERS ON GLASS/EPOXY THIN LAMINATE USING TAGUCHI ANALYSIS

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ABSTRACT

Experimental investigations were conducted to assess the influence of abrasive water jet machining (AWJM) parameters on the machining performance criteria namely surface roughness and kerf taper ratio. The approach was based on Taguchi's Method and Analysis of Variance (ANOVA) to optimize the AWJM parameters for effective machining of woven glass fibre reinforced epoxy composite. It was found that hydraulic pressure, standoff distance, abrasive mass flow rate and cutting orientation were the significant control factors; the cutting orientation was the insignificant control factor in controlling the machining performance criteria. Mathematical models were established using linear regression analysis to predict the surface roughness and kerf taper ratio in terms of the cutting parameters of AWJM. For effective machining of glass fibre reinforced epoxy composites, verification of the improvement in the quality characteristics has been made through confirmation tests with respect to the chosen reference parameter setting. It was confirmed that determined optimal combination of AWJM parameters satisfy the real need for machining of glass fibre reinforced epoxy composites in practice.

INTRODUCTION

Abrasive water jet machining (AWJM) process is one of the non-traditional machining processes that has been used extensively in various industry-related applications. The basic principles of abrasive water jet machining (AWJM) were reviewed in detail by Momber and Kovacevic (1998). This technology is less sensitive to material properties because it does not cause chatter, has no thermal effects, imposes minimal stresses on the workpiece, has high machining versatility and high flexibility. However, the AWJM process has some drawbacks; for instance, it may generate loud noise and a messy working environment (Choi and Choi, 1997; Wang and Wong, 1999).

The use of composite materials has gained increasing acceptance in our modern technology applications. Generally, composite materials have better mechanical properties such as low densities, high strength, stiffness and abrasion and impact and corrosion resistances. This can be done by combining two or more different materials which can produce a better combination of properties from both constituent phases (Callister, 2003; Komanduri *et al.*, 1991). Fibreglass is widely used as a reinforcement for composite material due to its unique characteristics which include high weight to strength ratio, is easily available and fabricated, has excellent corrosive resistant and design flexibility, is a good electrical insulator, has a high fatigue endurance limit, and is extremely cost-effective in certain manufacturing methods (Strong, 1989; Callister, 2003).

There are numerous related parameters and factors of the AWJM process that can influence the surface quality of the AWJ machined surfaces. However, in the present study only six factors are considered for analysis; 1 two-level factor and 5 three-level factors. By using conventional experimental methodology or a full factorial experiment, 486 distinct test conditions are needed to study all of the factors and their levels. Hence, it is neither economical nor practical to conduct a full-factorial experiment. It is therefore suggested to apply Design of Experiment (DOE) using Taguchi's orthogonal array to reduce the number of experiments to a more practical and affordable size.

MATERIALS AND METHOD

Materials

In these experiments, E-glass fibre of woven (plain weave) TGF-800 was used as reinforcement materials. The glass filament had a diameter of 10 μm. The width of the woven glass fibre strand was 4 mm and the thickness was 0.3 mm from direct roving. The matrix resin used was thermosetting epoxy resin (WM-215 TA) which was mixed with hardener WM-215 TB at a ratio of 4:1 (as recommended by manufacturer). The properties for both fibre glass and epoxy are shown in Table 1 (Ahmed Nazrin, 2005).

Sample Fabrication

Fibreglass/Epoxy laminates were prepared using the hand lay-up process. The woven fibre fabrics were cut into squares of 150 mm x 150 mm. The orientation of fibre (i.e. the length, the width, and the face) within the fabric was kept constant all the time during the lay-up process and they were considered as bidirectional laminates [0°/90°]. The layers were properly stacked into 9 plies so as to achieve approximately 5 mm thickness upon curing. The volume fraction of the laminate was around 0.50.

Equipment

The equipment used for machining the samples was Excel-CNC abrasive waterjet cutting machine equipped with an Ingersold Rand model of water jet pump with the designed pressure of 50,000 psi.

Experimental Design

The 6 machining parameters selected for the experimental design were abrasive types, hydraulic pressure, standoff distance, abrasive mass flow rate, traverse rate and cutting orientation (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 (Arola and Ramulu, 1993), Kevlar composite (Rahmah *et al.*, 2003), ceramic materials (Chen *et al.*, 1995), and structural metal alloys (Conner *et al.*, 2003). Based on Taguchi's Method DOE with 6 factors (5 three-level and 1 two-level factor), L_{18} (2^1 x 3^7) orthogonal array was selected for these experiments. L_{18} orthogonal array required 18 numbers of experiments to be conducted.

For each experimental run, the machining parameters were set to the pre-defined levels according to the orthogonal array (Table 3). The test specimen was machined according to a CNC programme in which a slot was machined 10 mm in length with full penetration as shown in Figure 1. Then it was machined 20 mm x 20 mm to detach the test specimen, thus, enabling the measurement of surface quality at the kerf face. All machining procedures were done using a single-pass cutting. All machined surfaces with respect to the weft direction as well as with respect to the warp direction are considered to be in the fibre orientation of [0°/90°], whereas, the +45° and -45° are those directions at positive angles of 45° and 315° respectively with respect to the traverse axis. Meanwhile, the +22.5° and -22.5° settings are those directions at positive angles of 22.5° and 337.5° respectively with respect to the traverse axis (Figure 1).

A surface roughness measuring device, SURFPAK SV-514, which has a cone-shaped diamond stylus with a diameter of 10 μm and 90° tip angle was used in this experiment. The measurement of surface roughness was obtained across the thickness of the test sample surface. Surface roughness profiles were taken from 0.5 mm above the bottom surface to 0.5 mm below the top surface to avoid the effects of jet exit and entrance respectively.

All measurements were acquired using 0.8 mm cutoff length. The values of surface roughness (R_a) were taken three times for each sample, so that their averages could be calculated in order to minimize the variability. The kerf taper ratio (T_R) was calculated by finding the ratio of top kerf

Table 1. Properties of the fibre and epoxy

Properties	Glass Fibre	Epoxy
Specific gravity, (g/cm^3)	2.54	1.20 – 1.30
Tensile strength, (GPa)	3.45	0.055 – 0.130
Modulus of elasticity, *E*, (GPa)	72.40	2.75 – 4.10
Poisson's ratio,	0.20	0.20 – 0.33
Linear coefficient of thermal expansion, mm/mm/°C	5 x 10^{-6}	50 – 80 x 10^{-6}

Table 2. Machining parameters and their respective levels

No.	Symbols	Machining Parameters	Level 1	Level 2	Level 3	Units
1	A	Abrasive types	Garnet	Aluminium Oxide	–	–
2	B	Pressure	137.9	206.9	275.8	MPa
3	C	Standoff distance	1.5	3.0	4.5	mm
4	D	Abrasive mass flow rate	2.5	5.0	7.5	g/s
5	E	Traverse rate	1.5	3.0	4.5	mm/s
6	F	Cutting orientation	0.0	22.5	45.0	Degrees

Table 3. The layout of L_{18} orthogonal array

Experiment No.	Control factors A	B (MPa)	C (mm)	D (g/s)	E (mm/s)	F (°)
1	Garnet	137.9	1.5	2.5	1.5	0.0
2	Garnet	137.9	3.0	5.0	3.0	22.5
3	Garnet	137.9	4.5	7.5	4.5	45.0
4	Garnet	206.9	1.5	2.5	3.0	22.5
5	Garnet	206.9	3.0	5.0	4.5	45.0
6	Garnet	206.9	4.5	7.5	1.5	0.0
7	Garnet	275.8	1.5	5.0	1.5	45.0
8	Garnet	275.8	3.0	7.5	3.0	0.0
9	Garnet	275.8	4.5	2.5	4.5	22.5
10	Aluminium Oxide	137.9	1.5	7.5	4.5	22.5
11	Aluminium Oxide	137.9	3.0	2.5	1.5	45.0
12	Aluminium Oxide	137.9	4.5	5.0	3.0	0.0
13	Aluminium Oxide	206.9	1.5	5.0	4.5	0.0
14	Aluminium Oxide	206.9	3.0	7.5	1.5	22.5
15	Aluminium Oxide	206.9	4.5	2.5	3.0	45.0
16	Aluminium Oxide	275.8	1.5	7.5	3.0	45.0
17	Aluminium Oxide	275.8	3.0	2.5	4.5	0.0
18	Aluminium Oxide	275.8	4.5	5.0	1.5	22.5

width (W_t) to bottom kerf width (W_b) as illustrated in Figure 1. Mitutoyo Profilometer was used for measuring both top and bottom kerf widths of the machined surfaces.

Based on the data acquired, the significant machining parameters were distinguished using Taguchi's Method's Analysis of Variance (ANOVA). Qualitek-4 (Roy, 2001) was the software used for automatic design and analysis of Taguchi's experiments. Regression analysis techniques were used to develop the empirical models of R_a and T_R respectively by using the SPSS v11.5 software (Norušis, 1991).

RESULTS AND DISCUSSION

Analysis of S/N Ratio

In Taguchi's Method, the signal to noise (S/N) ratio is expressed as a logarithm transformation of the Mean-Squared Deviation (MSD) for analysis of experimental results (Roy, 2001, Fowlkes and Creveling, 1995). The signal represents the desirable value of mean for the output characteristic, and the noise represents the undesirable value of square deviation for the output characteristic. A high S/N ratio indicates that there is high sensitivity with the least possible error of measurement. Hence, it is the ratio of the mean and the standard deviation, and can be expressed in decibels (dB).

Depending on the quality characteristics, R_a observes a lower value of better machining performance, known as smaller-the-better (STB) characteristic. The S/N ratio for the STB performance characteristic can be expressed as Equation 1.

$$S/N = -10 \log_{10} [\ 1/n\ \Sigma\, y_i^2\ ];\quad i = 1,2,\ldots,n \qquad \ldots\ldots (1)$$

As for the case of T_R, a nominal value of 1 is desirable since this particular value will occur when the W_t is equal to the W_b. Hence, the geometrical cut will have a higher degree of flatness and accuracy. Therefore, the T_R with a nominal value of 1 will provide better machining performance and it shall be known as nominal-the-best (NTB) quality characteristic. The S/N ratio for the NTB performance characteristic can be expressed as Equation 2.

$$S/N = -10 \log_{10} [\ 1/n\ \Sigma\, (y_i - 1)^2];\ i = 1,2,\ldots,n \qquad \ldots\ldots (2)$$

Table 4 shows the S/N ratios for R_a and T_R based on the orthogonal array matrix experiments.

Analysis of Variance

The analysis of variance (ANOVA) 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 quality characteristics. Through ANOVA, the degree of variation of each factor which causes relative to total variation observed in the result can be determined clearly. The total and factor sum of squares are the basic calculations derived from the S/N ratios.

The F-ratio or the variance ratio is the ratio between the effect control factor variance (the mean square due to a control factor) and the experimental error variance (the mean square due to experimental error). This ratio is used to test the significance of the factor effect. Tables 5 and 6 show the ANOVA and F-Ratio values on machining performance of R_a and T_R.

As suggested by Fowlkes and Creveling (1995), it is found that control factors B, C, D and F are relatively the most significant factors on the machining performance of surface roughness and these were consistent with others (Ramulu and Arola, 1994). They have almost equal effects on the machining performance. Meanwhile control factors A and E have a moderate effect on the machining performance of surface roughness. For a machining performance of kerf taper ratio, control factor A is the most significant factor. Control factors C, D and E may have moderate effects on machining performance. Control factors B and F are insignificant since the experimental error outweighs these control factors.

Analysis for Optimisation

The average S/N ratio for each factor level on machining performance of R_a and T_R are shown in Figures 2 and 3 respectively. It can be clearly observed that the most optimum level of machining parameters which produces the highest

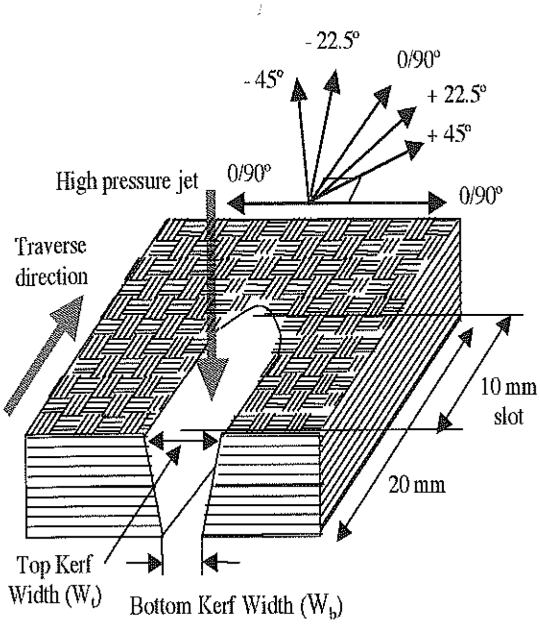


Figure 1. Cutting layout and orientation

Table 4. S/N ratios for R_a and T_R

Experiment No.	Woven Fibre	
	S/N Ratios for R_a	S/N Ratios for T_R
1	-12.176	20.653
2	-12.449	11.438
3	-12.752	12.268
4	-11.126	13.396
5	-12.059	11.862
6	-11.995	14.666
7	- 9.161	23.609
8	-11.003	21.346
9	-11.575	10.680
10	- 9.795	24.799
11	-11.809	18.501
12	-13.523	20.041
13	-12.315	31.394
14	- 8.011	36.575
15	-11.503	17.329
16	- 8.990	31.205
17	-11.287	16.528
18	-11.213	26.092

Table 5. ANOVA and F-ratio for R_a

Control Factor	Degree of Freedom	Sum of Square	Variance	F-Ratio	% of Contribution
1. A	1	1.90	1.90	3.30	5.48
2. B (MPa)	2	7.25	3.62	6.28	20.90
3. C (mm)	2	6.98	3.49	6.05	20.11
4. D (g/s)	2	6.46	3.23	5.60	18.63
5. E (mm/s)	2	2.70	1.35	2.34	7.79
6. F (°)	2	5.93	2.97	5.14	17.10
Error	6	3.46	0.58		9.98
Total	17	34.68			100.00

Table 6. ANOVA and *F*-ratio for T_R

Control Factor	Degree of Freedom	Sum of Square	Variance	F-Ratio	% of Contribution
1. A	1	374.09	374.90	17.63	38.22
2. B (MPa)	2	42.63	21.32	1.00	4.36
3. C (mm)	2	163.74	81.87	3.85	16.73
4. D (g/s)	2	165.68	82.84	3.90	16.93
5. E (mm/s)	2	95.74	47.87	2.25	9.78
6. F (°)	2	8.50	4.25	0.20	0.87
Error	6	127.57	21.26		13.03
Total	17	977.95			100.00

quality characteristic of surface roughness is the combination of factors A2B3C1D3E1F2 since Taguchi's Analysis observes the higher value of mean S/N ratio as a better quality characteristic. Meanwhile, quality characteristic of kerf taper ratio with a nominal value of 1 has the combination of A2B3C1D3E1F1 as the most optimum level of machining factors. It is also to be noted that the significant control factors with the highest F-ratio values from ANOVA tables are important in controlling the response of AWJM operation during the machining of glass/epoxy composite.

Confirmation Test

Confirmation tests were conducted using the optimal combinations of machining factors for each performance criterion. These confirmation tests were used to predict and verify the improvement in the quality characteristic for the machining of glass/epoxy composite with respect to the chosen initial parameters setting; A1B2C2D2E2F2.

Table 7 and 8 show the comparison of the predicted and actual machining performance for both R_a and T_R using their respective optimal cutting parameters. The predicted values of S/N ratios were calculated based on optimal cutting conditions as shown in Equation 3 (Fowlkes and Creveling, 1995).

$$S/N_{predicted} = S/N_{exp} + \sum_{i=1}^{i} (S/N_{mea} - S/N_{exp}) \qquad .....(3)$$

where S/N_{exp} is the overall average of S/N ratio for the entire orthogonal array, S/N_{mea} is the average of S/N ratio for each factor at optimum level and i is the number of main design parameters that affect quality characteristics.

Based on Table 7, it can be observed that the improvement of S/N ratio in respect to the initial parameter setting is about 3.75 dB or an improvement of about 35.11%. From Table 8, the improvement of S/N ratio is approximately 20.44 dB or an improvement in terms of the deviation of T_R (mm/mm) from its nominal value of 1.00 is about 95.28%. It was also noted that the predicted results of R_a and T_R at optimum cutting conditions using this Taguchi's Method were very close to the actual experimental results. This shows the repeatability of Taguchi's Method. Microscopic photography shows the surface roughness at optimum parameters setting (Figure 4b) is better than at initial parameters setting (Figure 4a).

Mathematical Model

Multiple linear regression analysis was used as the statistical method to build the mathematical models of the R_a and T_R. The functional relationship of these dependent variables and independent variables can be represented by the second order polynomial model with interaction as shown in Equation 4 (Montgomery, 2001).

$$y(x) = \beta_0 + \Sigma \beta_i \chi_i + \Sigma \beta_{ii} \chi_i^2 + \Sigma \Sigma \beta_{ij} \chi_i \chi_j \qquad ......(4)$$

where β_0 is a constant, β_i are the first order or linear effect coefficients, β_{ii} are the second order or quadratic effect coefficients, and β_{ij} are the interaction effect coefficients. The R_a and T_R models were developed in a similar form to Equation 4.

Based on the experimental data set, the R_a and T_R empirical models were developed and the coefficients of regression were determined using the SPSS software. These two models are based on 18 experiments. The models for R_a and T_R as in terms of machining parameters are shown in Equations 5 and 6 respectively.

$$R_a = 5.59 + -1.60 \times 10^{-2}\chi_2 + 7.89 \times 10^{-2}\chi_3^2 + -6.22 \times 10^{-2}\chi_4^2 + 7.62 \times 10^{-5}\chi_6^2 + 3.33 \times 10^{-6}\chi_1\chi_2 + -2.14 \times 10^{-4}\chi_1\chi_3 + -5.22 \times 10^{-5}\chi_1\chi_4 + -5.48 \times 10^{-6}\chi_1\chi_5 + 3.78 \times 10^{-6}\chi_1\chi_6 + -3.55 \times 10^{-4}\chi_2\chi_3 + -1.59 \times 10^{-3}\chi_2\chi_4 + 5.25 \times 10^{-2}\chi_3\chi_4 + 1.42 \times 10^{-2}\chi_3\chi_5 + -3.46 \times 10^{-3}\chi_3\chi_6 + 4.64 \times 10^{-2}\chi_4\chi_5 + -1.14 \times 10^{-3}\chi_4\chi_6 + -1.17 \times 10^{-3}\chi_5\chi_6 \qquad ......(5)$$

$$T_R = 1.26 + -4.43 \times 10^{-6}\chi_2 + -9.06 \times 10^{-3}\chi_3^2 + -6.26 \times 10^{-3}\chi_4^2 + -1.82 \times 10^{-4}\chi_6^2 + -8.31 \times 10^{-9}\chi_1\chi_2 + -1.49 \times 10^{-5}\chi_1\chi_3 + -2.91 \times 10^{-5}\chi_1\chi_4 + 1.33 \times 10^{-6}\chi_1\chi_5 + 5.13 \times 10^{-6}\chi_1\chi_5 + 1.36 \times 10^{-6}\chi_2\chi_3 + 2.24 \times 10^{-6}\chi_2\chi_4 + 1.86 \times 10^{-2}\chi_3\chi_4 + 3.36 \times 10^{-5}\chi_3\chi_5 + -7.26 \times 10^{-4}\chi_3\chi_6 + -2.62 \times 10^{-4}\chi_4\chi_5 + 9.97 \times 10^{-4}\chi_4\chi_6 \qquad ......(6)$$

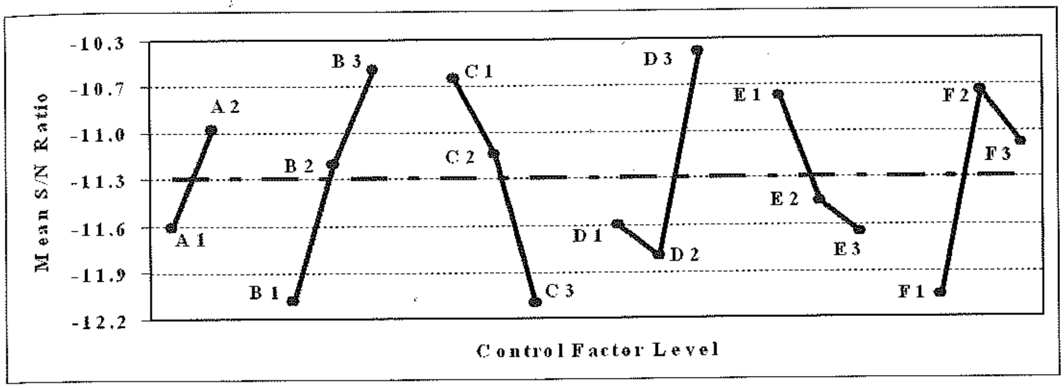


Figure 2. Average S/N Ratio (db) by control factor level for R_a

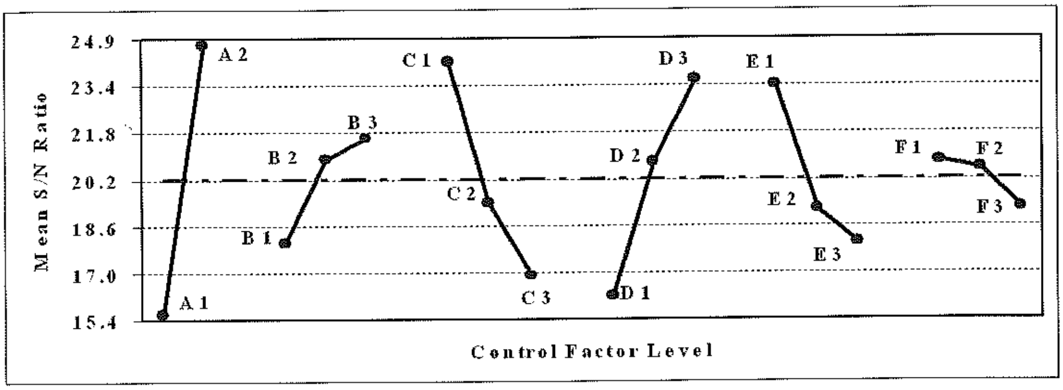


Figure 3. Average S/N Ratio (db) by control factor level for T_R

Table 7. Result of the confirmation test for R_a

Initial parameter setting	Optimal cutting parameters Predicted	 Experimental
A1B2C2D2E2F2		**A2B3C1D3E1F2**
S/N ratio (dB)	S/N ratio (dB)	S/N ratio (dB)
-11.06 (3.56 μm)	-7.6 (2.40 μm)	-7.31 (2.31 μm)

Table 8. Result of the confirmation test for T_R

Initial parameter setting	Optimal cutting parameters Predicted	 Experimental
A1B2C2D2E2F2		**A2B3C1D3E1F1**
S/N ratio (dB)	S/N ratio (dB)	S/N ratio (dB)
12.60	37.358	33.04
(1.233 mm/mm)	(0.986 – 1.014 mm/mm)	(0.989 mm/mm)

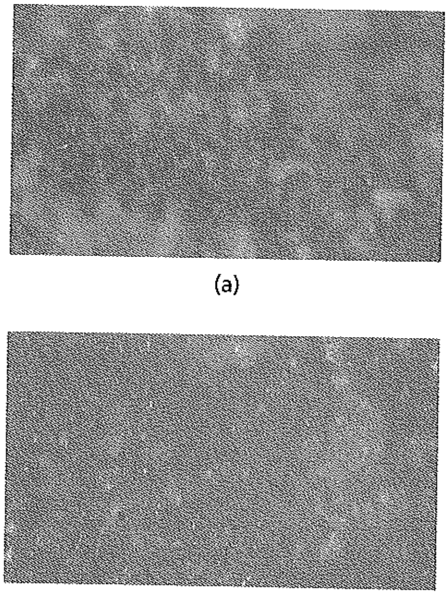
where χ_1 is the hardness value of abrasive materials (Knoop) (Momber and Kovacevic, 1998), i.e. Aluminium Oxide (2100 Knoop) and Garnet (1350 Knoop), χ_2 is the hydraulic pressure (MPa), χ_3 is the standoff distance (mm), χ_4 is the abrasive mass flow rate (g/s), χ_5 is the traverse rate (mm/s) and χ_6 is the cutting orientation (°).

The coefficients of determinations (R^2) were found to be 1.000 and 0.811 respectively for R_a and T_R models. There is reasonable correlation between the experimental and predicted values for both quality criteria as shown in Figure 5. The above mathematical models are useful in predicting the machining response of AWJM process during the machining of glass/epoxy laminate. A proper selection of machining parameters can be formulated to be used in practical works for manufacturing industries.

CONCLUSION

On the basis of the 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 thin woven glass/epoxy composite by the AWJM process as follows:

1. The hydraulic pressure (MPa), standoff distance (mm), abrasive Flow rate (g/s) and cutting orientation (°) are considered as significant machining parameters for controlling the R_a. Meanwhile the type of abrasives used alone is the most significant machining parameter for T_R. Adjusting these parameters would enable us to create the greatest effects on both quality criteria respectively.
2. The recommended parametric combinations for better surface finish and kerf taper ratio are A2B3C1D3E1F2 and A2B3C1D3E1F1 respectively where they show significant improvement compared to the initial cutting parameters.
3. The mathematical models successfully predicted the surface roughness and kerf


(a)

(b)

Figure 4. Microscopic photographs of glass/epoxy surfaces at 200X, (a) AWJ machined surface at initial parameters setting, $R_a = 3.56$ μm and (b) AWJ machined surface at optimal parameters setting, $R_a = 2.31$ μm.

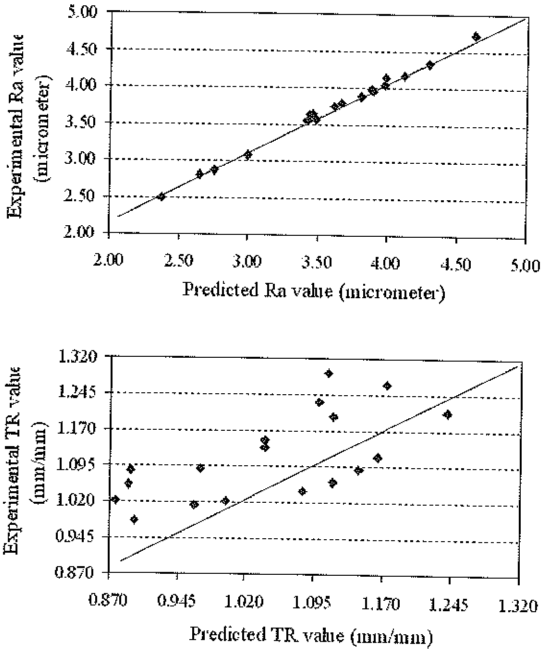


Figure 5. Predicted versus experimental values of R_a and T_R (line drawing indicate the ideal cases)

taper ratio for an AWJ machined glass/epoxy laminate with a thickness of approximately 5 mm and can be used for determining cutting parameters for the tailored surface quality.

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