A abrasive water jet machining of CFRPs: single response optimization using taguchi method optimization

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Abstract. Taguchi method was applied to assess and optimize machining parameters and their effect on kerf characteristics during abrasive water jet machining (AWJM) of carbon fiber reinforced polymeric composites (CFRPCs). The main responses selected for these analyses are kerf width, kerf taper, metal removal rate, and surface roughness, the consistent machining parameters focussed for this study are abrasive flow rate, pressure, traverse rate, thickness of the workpiece and standoff distance, each parameter has three levels. Twenty-seven experiments were conducted on a typical CFRP composite workpiece materials based on Taguchi L27 design. The response curves and response tables were used to assess the data obtained to control the major significant process factors statistically affecting the kerf characteristics. The optimal settings of process parameters for each response are set up. From the analysis, it was detected that the percentage contribution of the control factors affecting the kerf width is standoff distance, workpiece thickness, abrasive flow rate, traverse rate, and pressure correspondingly. The results exposed that the thickness, feed rate, and standoff distance were the most significant factors affecting the kerf taper, metal removal rate, and surface roughness respectively.

Introduction
Abrasive water jet machining (AWJM) is one of the most newly developed non-traditional cutting processes. It uses a fine jet of ultrahigh-pressure water and abrasive slurry to cut the board material by means of corroding. AWJ cutting is being progressively used to machine a wide-ranging of metals and non-metals, mainly ‘difficult-to-cut’ materials such as ceramics, marble, and fiber-reinforced polymeric composites, due to its various different advantages over other technologies such as no thermal distortion, high machining adaptability, ability to contour and small cutting force [1-2]. Since the introduction of the AWJ cutting technology for commercial use, a large amount of researches and progress has been made to discover its applications and related science [4-24]. However, this technology is still below progress and there are many features of the technology that persist to be fully understood [8]. The work presented in this paper describes experimental work that has been undertaken with the objective of improving the current absence of understanding in the AWJM of CFRP composites. The experimental results can be used to provide approvals for the selection of cutting parameters for AWJM applications. Definitely, the objective of the research described in this study is as follows: To achieve a detailed experimental study of the kerf characteristics when AWJM of CFRPCs to gain a complete understanding of the effects of several major process variables and to give optimum cut quality using Taguchi method.
Experimentation
The experimental work was accompanied on abrasive water jet cutting machine in which the tests were made is an OMAX 5555 jet machining center (figure 1). This model cuts multifarious flat parts out of most materials directly from a CAD drawing or DXF file. It includes a completely sealed and safe ball screw drive system, providing strength and dependability while offering high correctness. Mixing tube of 0.762mm in diameter and 76.2mm in length were used to produce the AWJ. Garnet abrasives of 80 mesh (0.18 mm average diameter and 4.1 g/cm3 density) were applied. The CFRP composite material specimens used in this study were fabricated by stacking prepare, which is composed of one-way carbon fiber and epoxy resin bidirectional (0–90) and specimens were stacked to a total of 12, 24 and 36 plies respectively. The specimens were fabricated by compressing the material at a curing temperature of 125 °C using a heater located inside a cavity, with a curing time of 180 min and a forming pressure of 5 kg/cm2 as revealed in figure 2. The mechanical properties of the carbon-fiber prepares are publicized in Table 1. The specimen was 50x50 mm in vertical and horizontal direction figure 3.

Figure 1. OMAX 5555 Jet Machining Centre

Figure 2. Stacking process for CFRPCs

The specimen was 50x50 mm in vertical and horizontal centring. Different workpiece geometries are planned to study the kerf characteristics in the straight cutting and profile cutting or contouring as presented in figure 3. The first geometry design is a straight cutting (kerf) as illustrated by figure 3. This design allows to measure the surface roughness on the depth of cut and to measure the distance between each cut side (kerf width) in the upper and lowest positions while providing the capability to picture the angle formed (kerf taper angle). MRR can be calculated. The second geometries design are square opining, hole opening, and external curving. The two holes characterized in the center of the plate were made for the resolve of holding it to the stand in the coordinate machine. In this paper, the experimental study is restricted to straight cutting under a range of AWJ process parameters.

Table 1. Mechanical properties of the Carbon-Fibre Sample

| Properties           | Value |
|----------------------|-------|
| Tensile strength (MPa) | 5490  |
| Tensile modulus (MPa) | 294   |
| Elongation (%)        | 1.9   |
| Density (g/cm³)       | 1.81  |

Figure 3. Geometry of the Workpiece.
1.1. Experimental Design Methodology
A Taguchi orthogonal array is used in this investigation as an experimental plan. For ease and avoiding lengthy statement, the concept of Taguchi was offered and employed in Ross [3]. Table 2 illustrates the cutting parameters and their levels reflected for the experimentation on this paper. The parameters and levels were selected agreeing to the review of some papers [18-23] that has been recognized on AWJM on CFRPCs. Rendering to the Taguchi method, an L27 orthogonal array was working for the experimentation. Based on this, a total number of 27 experiments were done, each having a unlike combination of cutting parameters as shown in table 3. The responses were noted for each experimental run.

| Parameters                  | symbol | Level 1 | Level 2 | Level 3 |
|-----------------------------|--------|---------|---------|---------|
| Material Thickness (mm)     | T      | 4       | 8       | 12      |
| Water Pressure (MPa)        | P      | 100     | 200     | 300     |
| Traverse speed (mm/s)       | V      | 1       | 3       | 5       |
| Abrasive flow rate (g/min)  | AFR    | 100     | 200     | 300     |
| Standoff distance (mm)      | SOD    | 2       | 4       | 6       |

1.2. Data Acquisition of Kerf Characteristics
Kerf width: A Portable 600x 3.6 MP digital microscope was used to measure the kerf width in upper and bottom positions. The measurements are occupied in three points: near to the upper edge, in the middle, near to lower edge of the Kerf and the usual value of measurements was used and preserved as the result of a single experiment for analysis (Figure 4).
Kerf taper: It was expected that in AWJ cutting the two kerf walls might not be regular due to the jet tailback effect. Figure 5. displays the kerf geometry.
The kerf taper can be acquired by measuring the upper and bottom kerf width and changing to taper kerf trend by the following relation:

$$\theta = \tan^{-1}\left(\frac{W_t - W_b}{2T}\right)$$  (1)
Where, \( W_t \), \( W_b \), and \( T \) are the upper kerf width, bottom kerf width, and workpiece thickness correspondingly.

Metal Removal Rate (MRR): MRR for each experiment was calculated using the next formula:

\[
MRR = 0.5 (W_t + W_b). T. V
\]

Where \( V \) is cutting speed and unit for MRR is \( \text{mm}^3/\text{sec} \).

![Figure 4. Schematic Illustration of kerf image.](image1)

![Figure 5. Schematic Illustration of Kerf Geometry.](image2)

Surface Roughness (Ra): The surface texture parameter for the Kerf throughout this investigated was the arithmetic mean roughness (Ra).

The measurements were taken at the direction of the cut in three areas: near to the upper edge, in the middle, near to lower edge in the center of the Kerf and the average value of measurements was used and treated as the result of a single experiment for analysis, figure 6. Figure 7 illustrations the kerf image.

The results of the four cut quality characteristics of kerf specifically, upper and bottom kerf width, taper angle, MRR and Ra for each of 27 trials are listed in Table 4. conferring to the performed experiment design.

| Exp. No. | Kerf (mm) | Taper Angle \( \theta \) | MMR (mm\(^3\)/s) | SR (\( \mu \)m) | Exp. No. | Kerf (mm) | Taper Angle \( \theta \) | MMR (mm\(^3\)/s) | SR (\( \mu \)m) |
|----------|-----------|----------------|--------------------|--------------|----------|-----------|----------------|--------------------|--------------|
| 1        | 1.04      | 0.32          | 5.14               | 3.58         | 15       | 1.58      | 0.86          | 2.57               | 49.1         |
| 2        | 1.17      | 0.33          | 6.05               | 3            | 16       | 1.36      | 0.89          | 1.68               | 9.04         |
| 3        | 1.43      | 0.38          | 7.47               | 3.96         | 17       | 1.55      | 1.05          | 1.77               | 31.26        |
| 4        | 1.48      | 0.97          | 3.64               | 4.9          | 18       | 1.16      | 0.71          | 1.61               | 37.73        |
| 5        | 1.62      | 1.01          | 4.34               | 4.35         | 19       | 1.76      | 1.16          | 1.42               | 17.53        |
| 6        | 1.05      | 0.60          | 3.20               | 16.62        | 20       | 1.61      | 1.01          | 1.45               | 47.29        |
| 7        | 1.77      | 1.07          | 4.98               | 5.69         | 21       | 1.23      | 0.88          | 0.82               | 63.67        |
| 8        | 1.21      | 0.83          | 2.75               | 12.3         | 22       | 1.71      | 1.29          | 0.99               | 18.06        |
| 9        | 1.30      | 0.86          | 3.11               | 21.65        | 23       | 1.39      | 0.94          | 1.07               | 42.21        |
| 10       | 1.56      | 1              | 2.00               | 10.24        | 24       | 1.49      | 1.02          | 1.10               | 75.45        |
| 11       | 1.22      | 0.56          | 2.35               | 21.34        | 25       | 1.45      | 1.22          | 0.55               | 16.06        |
| 12       | 1.14      | 0.31          | 2.98               | 29.1         | 26       | 1.54      | 1.17          | 0.87               | 48.82        |
| 13       | 1.50      | 0.93          | 2.05               | 9.77         | 27       | 1.51      | 0.87          | 1.52               | 71.55        |
| 14       | 1.19      | 0.86          | 1.18               | 24.78        |          |           |               |                   |

Table 4. Results of experimental plan.
3. Result and Discussion

1.3. Effect of Process Variables on Kerf Top Width ($W_t$)

The average values of $W_t$ for each parameter at levels 1, 2, and 3 for the raw data are schemed in figure 8. It shows that the $W_t$ increases with the increase of T, AFR, and SOD where the standoff distance adopts the area of cutting which increases or decreases the impact area (whereas deviation of jet takes place with increase in stand-off distance), besides this, the effect of stray abrasive particles is prominent with high standoff distance with the rise of abrasive mass flow rate, cutting ability of jet that rises kerf top width and damage the surface. During increasing the abrasive particles (AFR), they own more energy to cut the material and they constantly lose the energy during decreasing its quantity. By the fact of increasing T, the time of piercing rise causes wider top kerf. Also, $W_t$ decreases with increase in V due to less abrasive impingement at high traverse rate and results in less overlying of machining action, which reduces the kerf top width whereas the effect of water pressure is not important on $W_t$. It is also obvious that $W_t$ is minimum at first level of SOD and maximum at third level of SOD.

The response table 5 shows the average of $W_t$ (S/N data) and its proportion contribution. The table contains ranks based on delta statistics, which equate the relative magnitude of effects. The delta statistic is the highest minus the deepest average for each factor. Minitab allocates ranks based on delta values; rank 1 to the highest delta value, rank 2 to the second-highest, and thus on. The ranks designate the relative importance of each factor to the response. The ranks and the delta values show that SOD has the highest effect on $W_t$ and is tailed by T, AFR, V, and P in that order. From the analysis, it was saw that the percentage contribution of the control factors affecting the $W_t$ is SOD (33.96%), T (18.81%), AFR (18.78%), V (18.35%), and P (10.08%) one-to-one. As $W_t$ is the “lower the better” type quality characteristic, it can be seen from figure 7 that the first level of T, first level of P, third level of V, first level of AFR, and first level of SOD offer minimum value of $W_t$. The S/N data analysis (Table 5) also advises the same levels of the variables (T = 4 mm, P = 100 MPa, V= 5 mm/sec, AFR = 100 g/min and SOD = 2 mm) as the best levels for minimum $W_t$. Because this combination parameters are
selected from the response table (table 5) conferring to Taguchi analysis, and this combination parameters are not found in the orthogonal array (table 3), the confirmation test analysis for $W_t$ is processed. The result of confirmation test analysis is associated with the initial condition of setting parameters. It is clear from table 4, that experiment No.7 has the poorest $W_t$ value (1.77 mm) compared to the other experiments. therefore, it can be decided that experiment No. 7 possesses initial setting parameters. Table 6 displays the comparative results of the near-optimum setting parameters ($T= 4 \text{ mm}, P=100 \text{ MPa}, V= 5 \text{ mm/sec}, \text{AFR} = 100 \text{ g/min and SOD} = 2\text{mm}$) and initial setting parameters ($T = 4 \text{ mm}, P = 300 \text{ MPa}, V= 1 \text{ mm/sec}, \text{AFR} = 300 \text{ g/min and SOD} = 6 \text{mm}$). For the single performance characteristic, the $W_t$ is reduced from 1.77 mm to 1.03 mm. The forecast (calculated) of $W_t$ using the optimal level setting parameters can be calculated from Minitab 17. The conforming improvement in $W_t$ is 58%.

Table 5. Response for Signal to noise ratios of kerf width.

| Level | T     | P     | V     | A.F.R  | S.O.D  |
|-------|-------|-------|-------|--------|--------|
| 1     | -2.434* | -2.505* | -3.521 | -2.267* | -1.906* |
| 2     | -2.641  | -3.140  | -2.807 | -2.976  | -2.742  |
| 3     | -3.618  | -3.047  | -2.365* | -3.450  | -4.045  |
| Delta | 1.185   | 0.635   | 1.156  | 1.183   | 2.139   |
| Rank  | 2       | 5       | 4      | 3       | 1       |
| contribution | 18.81% | 10.08%  | 18.35% | 18.78%  | 33.96%  |

Table 6. Results of confirmatory experiment of kerf width

| Worst value (Exp. No.7 Table.4.5) | $W_t = 1.772 \text{ mm}$ |
|------------------------------------|---------------------------|
| Near optimum combination           | $T=4 \text{ mm}, P=100 \text{ MPa}, V= 5 \text{ mm/sec}, \text{AFR} = 100 \text{ g/min and SOD} = 2\text{mm}$ |
| Predicted value (TAGUCHI)          | $W_t = 0.948 \text{ mm}$ |
| Experimental value                 | $W_t = 1.03 \text{ mm}$ |
| Improvement %                      | $1.029/1.772 = 58\%$ |

Figure 9 displays that there is very weak interaction between the process parameters in affecting the $W_t$ since the responses at different levels of process parameters for a given level of parameter value are nearly parallel. It can be realized from figure 10 that the data follow a roughly straight line in normal probability plot display that the data are normally scattered.

Figure 9. Effects of Process Parameters Interactions on $W_t$ (Raw Data).

Figure 10. Normal Probability Plot for Kerf Top Width.
1.4. Effect of Process Variables on Kerf Taper ($K_t$)

Figure 11 illustrates that the $K_t$ drops with the increase of T and P but increases with rise in AFR and SOD which the effect of V is frailly on $K_t$. During the jet penetrates into the material, the jet loses its kinetic energy when moving from upper surface to bottom surface, which reduced cutting ability constantly cases the kerf taper. The parameters similar jet pressure and feed rate decide the kinetic energy and the cutting time for the process and that control $K_t$. But the standoff distance agrees the area of cutting which rises or decreases the impact area cases high $K_t$ at high level of SOD, with increase T the angle of cut by the jet penetration reduced cases little $K_t$.

Table 7 displays the average of $K_t$ (S/N data) and the optimal level setting parameters and its ratio contribution. Table 8 shows the forecast (calculated) value of $K_t$ and the conforming improvement.

Table 7. Response for signal to noise ratios of kerf taper.

| Level | T   | P    | V    | A.F.R | S.O.D |
|-------|-----|------|------|-------|-------|
| 1     | -12.6725 | -8.3357 | -6.010 | -6.1594 | -4.98* |
| 2     | -5.8401 | -5.7167 | -5.975* | -5.5393* | -6.1183 |
| 3     | -0.3958* | -4.8559* | -6.922 | -7.2097 | -7.8039 |
| Delta | 12.2767 | 3.4798 | 0.947 | 1.6704 | 2.8178 |
| Rank  | 1   | 2    | 5    | 4   | 3     |
| contribution | 57.93% | 16.42% | 4.4% | 7.88% | 13.29% |

Table 8. Results of confirmatory experiment of kerf taper

| Worst value (Exp. No.3 Table.4) | $K_t$ = 7.477° |
| Near optimum combination | T=12mm, P =300MPa, V= 3mm/sec, AFR = 200 g/min and SOD 2 mm |
| Predicted value (TAGUCHI) | $K_t$=0.01° |
| Experimental value | $K_t$. = 0.803° |
| Improvement % | 0.803563/7.477 = 10.73% |

Figure 12 displays that there is very frail interaction between the process parameters in touching the $K_t$ since the responses at different levels of process parameters for a given level of parameter value are virtually parallel. It can be understood from figure 13 that the data follow a roughly straight line in normal probability plot indicates that the data are normally scattered.
1.5. Effect of Process Variables on Metal Removal Rate (MRR)

Figure 14 displays that the MRR rises with the rise of T and V, and the effects of both P, AFR and SOD is frailly on MRR. By the fact of growing kinetic energy due to an increase in V, T, and P that give higher MRR which rises in feed rate and pressure the abrasive particle becomes less time to cut the higher material thickness and new particles arrive in cutting region. Also, aids to remove more volume of material. Also, the effect of SOD is frail because the deviation in jet and low kinetic energy of the abrasive particles due to more distance between the jet and the workpiece beside the sharp cutting of the material is not possible, the cutting ability reduced during traveling owing to distance travelled that reduces its capability of material removal but SOD increase the cutting region and remove higher MRR.

Table 9 displays the average of MRR (S/N data) and the optimal setting parameters and its percentage contribution. Table 10 shows the forecast (calculated) value of MRR and the corresponding progress. The near optimum setting parameters (T = 12 mm, P = 300 MPa, V = 5 mm/sec, AFR = 300 g/min and SOD = 6 mm).

| Level | T   | P   | V   | A.F.R | S.O.D |
|-------|-----|-----|-----|-------|-------|
| 1     | 19.87 | 24.83 | 18.98 | 25.21 | 25.06 |
| 2     | 26.46 | 26.54 | 27.67 | 26.25 | 25.79 |
| 3     | 31.63*  | 26.57* | 31.29* | 26.49* | 27.10* |
| Delta | 11.76 | 1.74 | 12.31 | 1.27 | 2.04 |
| Rank  | 2    | 4   | 1   | 5    | 3    |

Table 9. Response for Signal to noise ratios of MRR.
Table 10. Results of confirmatory experiment of MRR.

| Worst value (Exp. No.1 Table4) | MRR = 2.72 mm |
| Near optimum combination       | P =300 MPa, V= 5 mm/sec, AFR = 300g/min and SOD = 6 mm |
| Predicted value (TAGUCHI)      | 76.32 mm³/sec |
| Experimental value             | MRR= 75.69 mm³/sec |
| Improvement %                  | 2.72/75.69 = 3.59% |

Figure 15 displays that there is very frail interaction between the process parameters in affecting the MRR since the responses at different levels of process parameters for a given level of parameter value are nearly parallel. It can be understood from figure 16 that the data follow an approximately traditional line in normal probability plot designates that the data are normally distributed.

1.6. Effect of Process Variables on Surface Roughness ($R_a$)

Figure 17 displays that the $R_a$ rises with the increase of T, V, and SOD, and decreases with an increase in P where lower pressure deteriorated the finish on the cut surface by creating lays and flaws with observed strong scratches and grooves, resulting in a poor finish. Also, with increasing the area of cut surface by increasing T there is more lays and flaws and the surface waviness produced a large difference between the peak and valley from the mean line, resulting in a poor finish. The excessive abrasives penetrate into the layers of material which result in abrasive embedment. Abrasive embedment is mainly observed at high AFR and low SOD. At low SOD, abrasives cannot accelerate with high-speed water jet which causes abrasives to impinge on material with low kinetic energy. These abrasives penetrate into the layers and machined surface cases rough surface. There are small effects of AFR. which the jet lag at higher V resulted because of insufficient time for cutting the CFRP. Thus, the fibers that poked out from the cut surface got forced up with the stylus probe during measurement, increasing the roughness. With the overlapping of machining action and also reduced number of abrasive particles to impinge on surface. Also, at low pressure, the surface waviness produced a large difference between the peak and valley from the mean line, resulting in a poor finish. However, the increased energy at high pressure improved the cutting efficiency and produced a smooth surface. Figure 18 displays the defects and damage in the cut surface.
Figure 17. Effects of Process Parameters on R<sub>a</sub> (Raw Data).

Figure 18. Stacking process for CFRPCs.

Table 11 displays the average of R<sub>a</sub> (S/N data) and the optimal setting parameters and their percentage contribution. Which Table 12 shows the predicted (calculated) value of R<sub>a</sub> and the conforming improvement.

Table 11. Response for signal to noise ratios of surface roughness.

| Level | T   | P   | V   | A.F.R | S.O.D |
|-------|-----|-----|-----|-------|-------|
| 1     | -10.35* | -11.91 | -10.50* | -11.46 | -10.61* |
| 2     | -11.71 | -11.41 | -11.45 | -11.12* | -11.31 |
| 3     | -11.84 | -10.58* | -11.94 | -11.31 | -11.98 |
| Delta | 1.49 | 1.33 | 1.44 | 0.34 | 1.37 |
| Rank  | 1   | 4   | 2   | 5   | 3    |
| contribution | 24.95% | 22.27% | 24.12% | 5.69% | 22.94% |

Table 12. Results of confirmatory experiment of surface roughness.

| Worst value (Exp. No.12 Table.4.5) | R<sub>a</sub> = 5.09 µm |
| Near optimum combination | T=4 mm, P =300 MPa, V= 1mm/sec, AFR = 200 g/min and SOD 2 mm |
| Predicted value (TAGUCHI) | R<sub>a</sub> = 2.301 µm |
| Experimental value | R<sub>a</sub> = 2.498 µm |
| Improvement % | 2.698 /5.09 = 53.96% |

Figure 19 shows that there is very weak interaction between the process parameters in affecting the R<sub>a</sub> since the responses at different levels of process parameters for a given level of parameter value are greatest parallel. It can be seen from figure 20 that the data follow an approximately traditional line in normal probability plot indicates that the data are normally scattered.
Conclusions

In cutting CFRPs using AWJM, numerous process parameters have effect on the performance measures. The effect of process variables on the characteristics of straight cutting was discussed. The optimal process parameters are found for various performance measures using the Taguchi design of experiment methodology. (single response optimization). The following assumptions can be drawn from the results of the present work:

1) SOD has the utmost effect on $W_t$ and is trailed by T, AFR, V, and P in that order. From the analysis, it was detected that the percentage contribution of the control factors affecting the $W_t$ is SOD (33.96%), T (18.81%), AFR (18.78%), V (18.35%), and P (10.08%) respectively.

2) $W_t$ rises with the increase of T, AFR, and SOD, also, $W_t$ decreases with rise in V.

3) $K_t$ decreases with the rise of T and P, also, $K_t$ increases with rise in AFR and SOD. V has a very frail influence.

4) There is a very frail interaction by the process parameters on affecting the $K_t$.

5) MRR increases with the increase of T and V, and the outcome of P, AFR and SOD are frailly on MRR.

6) From the analysis, it was noticed that the percentage contribution of the control factors affecting the MRR is V (42.27%), T (40.38 %), SOD (7.00%), P (5.97%), and AFR (4.36%) respectively.

7) $R_a$ rises with the increase of T, V, and SOD, and decreases with an increase in P.

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