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Optimal Abrasive Jet Machining Parameters for Glass Fiber Reinforced Plastics

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Abstract

Abrasive jet machining (AJM) is a best choice for processing of glass fiber reinforced plastics (GFRP). Inherent to the nonlinear behavior of performance characteristics during repeated experiments are inevitable variations, attributed to measurement errors and unknown influencing input variables. This study employs the Taguchi method with an orthogonal array to systematically identify optimal input variables through a limited number of experiments. The paper introduces a direct and reliable Taguchi-based multi-objective optimization approach, aiming to determine a range of performance characteristics—such as material removal rate (MRR), overcut (OC), and taper cut (TC)—for optimal AJM parameters (including pressure, stand-off-distance, and nozzle diameter) specifically tailored for GFRP. The developed empirical relationships for MRR, OC, and TC in terms of AJM parameters were validated with experimental data. This research contributes to advancing the precision and efficiency of AJM processes for GFRP, providing valuable insights for industrial applications.

Keywords: Abrasive Jet Machining; Abrasive Pressure; Reinforced Plastic with Glass Fibers; Material Removal Rate; Stand-off Distance; Inclined Cutting.

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INTRODUCTION

Machining high-strength and high-temperature resistant (HSTR) materials conventionally poses challenges. Non-conventional methods like laser beam machining often result in thermal distortion and low productivity. To erode material from the work surface, a high-velocity jet of abrasives in AJM (abrasive jet machining) is used with highly pressurized air or gas. Nozzle plays a significant role by converting pressure energy into kinetic energy and directing the abrasive jet toward the work surface at the desired impingement angle. As the hard abrasive particles impact, they gradually remove material through erosion. AJM stands out for its high flexibility, absence of thermal distortion, minimal cutting forces, machining versatility, lack of a heat-affected zone (HAZ), and high productivity. These advantages have led to widespread applications in aerospace, automobile, marine, and other industries. AJM is not only used for machining but also for cleaning hard and brittle materials. Franz introduced this cutting-edge technology for laminated paper tubes in 1968, evolving into a commercial system by

1983. Water jet pioneer John Olsen explored AJM as an alternative to conventional machining in 1990 [1].

The use of high-strength, lightweight, corrosion-resistant glass fiber-reinforced plastic (GFRP) has expanded in aerospace, automobile, and marine industries. AJM has undergone extensive testing in glass machining [2–10]. Researchers, such as El-Domiaty et al. [2], conducted drilling experiments using sand as an abrasive. They found that the material removal rate (MRR) increases with larger particle sizes, higher pressure, and larger nozzle diameters. Chandra [3] and Kandpal et al. [4] reported increased MRR with higher pressure in drilling tests. Vadgama et al. [5] and Padhy and Nayak [6] conducted drilling tests and observed that MRR initially increases and then decreases with rising pressure and stand-off-distance up to a certain limit. Sharma and Deol [7] discovered that taper cuts and overcuts of holes decrease with increased pressure and nozzle diameter, and decreased stand-off-distance.

Further investigations by Grover et al. [8] indicated that MRR decreases with a reduction in impact angle and grain size. Fan et al. [9] developed predictive mathematical models for MRR in micro-machining of holes and channels on glasses by AJM. Their findings suggest that MRR increases with air pressure and stand-off-distance and slightly decreases with abrasive mass flow rate and machining time. Zhang et al. [10] explored micro-abrasive intermittent jet machining for drilling small holes, ensuring the removal of abrasive particles to prevent system blockage. Additionally, extensive studies using the AWJM process have been conducted on CFRP composites [11–16], Nylon-6 GFRP composites [17], Carbon epoxy composites [18], CGFR hybrid composites [19], and metal matrix composites [20–24].

Sharma and Deol [7] designed an AJM setup and executed experiments on Glass Fiber-Reinforced Plastic (GFRP), as depicted in Figure 1. The study focused on three key input process parameters: abrasive pressure, stand-off distance, and nozzle diameter. Material removal rate (MRR: change of workpiece weight after machining with time) was assessed, and measurements were taken for overcut (OC: half the difference in the diameters of the workpiece and the nozzle) and taper cut (TC: half the difference in the upper and lower cuts of the workpiece). The machining process employed silicon carbide with a mesh size of 150 and a grit size of 70 μm on a 4 mm thick GFRP sheet (sized 400 x 400 mm), subsequently cut into 4 pieces of 50 × 50 mm.

To systematically explore the impact of the AJM process parameters, Taguchi's L9 Orthogonal Array (OA) was adopted, assigning three levels to each of the three AJM parameters. The parametric optimization on GFRP was conducted using Minitab software. Subsequently, an ANOVA (analysis of variance) was carried out after applying S/N (signal-to-noise) ratio transformation by converting multiple test run data to a single value for each MRR, OC, and TC. Taguchi recommended the S/N ratio transformation to account for scatter in the data obtained from several repetitions of each test run.

While S/N ratio transformations effectively consider data scatter, offering a single value for each test run's performance indicator, it's important to note that the additive law [25] relies on mean values to estimate an output response [26, 27]. To address this, the present paper adopts a modified Taguchi-based multi-optimization approach, aiming to estimate the anticipated range of the performance indicator (PI) at specified input AJM process variables. Notably, the test results [7] fall within the anticipated range, confirming the reliability of the approach. The application of the S/N ratio transformation, as employed by Sharma and Doel [7], introduces an additional computational step in the analysis. This modified Taguchi-based approach enhances the understanding of the expected variation in the performance indicator under specific AJM process conditions, contributing to a more comprehensive and nuanced optimization strategy.

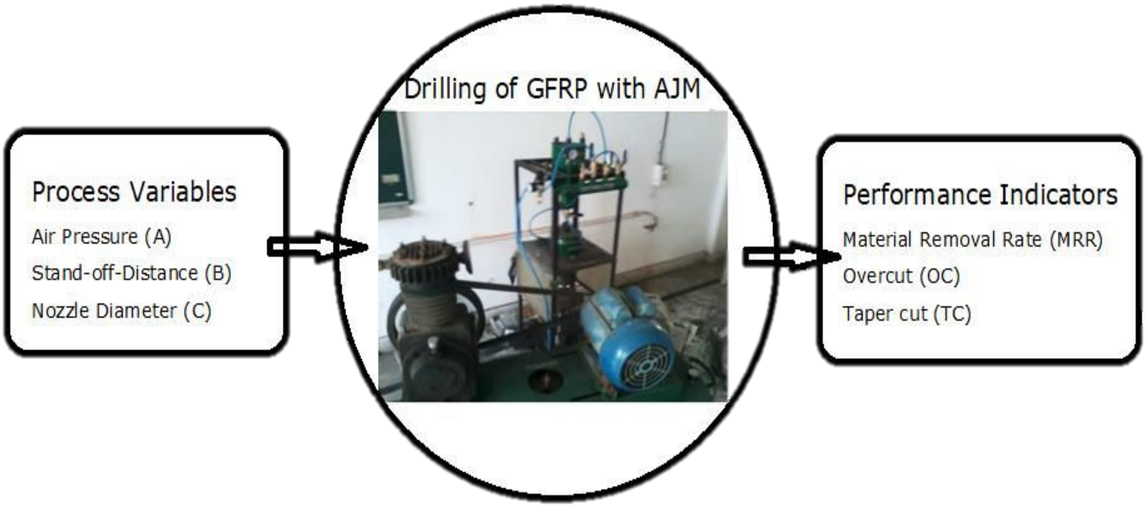

Figure 1. Process parameters and performance indicators in drilling of GFRP with AJM [7].

ANALYSIS OF VARIANCE (ANOVA)

Taguchi's Design of Experiments (DOE) [25] has proven effective in numerous machining processes [26, 27]. This method relies on an OA to conduct a limited number of tests. Through the data obtained from these tests, it becomes possible to generate information for all possible combinations of process variable levels, akin to a fully factorial design of experiments. This approach significantly reduces the need for trial tests and associated costs. The importance of process variables can be determined through ANOVA, facilitating the development of empirical relationships between performance indicators and process variables.

In a study by Sharma and Doel [7], AJM was applied to GFRP, with 3 levels assigned to each input parameter shown in Table 1(a). The performance indicators (PIs) in Table 1 (b) are MRR (material removal rate), OC (overcut), and TC (taper cut), corresponding to the assigned AJM parameters under the L9 Orthogonal Array, are detailed in Table-1. The minimum number of experiments (N_{Tests}) and assigned levels (n_L) align with the number of process variables (n_{PV}) [25]:

$$N_{Tests} = 1 + n_{PV}(n_L - 1) \tag{1}$$

In the current L9 OA, the equation (1) indicates that 9 tests and 3 levels are accommodated, allowing for 4 process variables. However, reference [7] focuses on only 3 AJM parameters. To address this, a fictitious factor (D) is introduced in Table 1(b), following the approach outlined in References [26, 27]. The ANOVA results in Table 2 reveal that the input parameters A, B, C, and the fictitious parameter (D) contribute 7.9%, 14.4%, 64.2%, and 13.5%, respectively, to MRR. For OC, the contributions are 19.1%, 14.1%, 64.1%, and 2.6%, while for Taper Cut (TC), they are 16.5%, 28.5%, 8.1%, and 46.9%. According to the ANOVA table, the optimal AJM parameters for achieving maximum MRR, minimum OC, and TC are denoted as $A_3B_1C_3$, where subscripts indicate the levels of AJM parameters. In the case of different optimal AJM parameters, a multi-objective optimization approach is necessary to specify a set of AJM parameters that simultaneously achieve maximum MRR, minimum OC, and minimum TC.

MRR, *OC* and *TC* are three different PIs. They must be functionally represented in non-dimensional form. The maximum values of *MRR*, *OC* and *TC* evaluated from the ANOVA Table 2 using the additive law (2) are: MRR_{max} =0.2922 gms/min; OC_{max} =2.6567 mm; and TC_{max}= 1.4567 mm

Assuming the Performance Indicator (PI) as Θ, and following the additive law [25], one can express:

Table 1. The levels of AJM parameters and Performance Indicators (PIs) such as MRR, OC, and TC according to the L9 Orthogonal Array.

(a) AJM process parameters

Parameters	***Designation***	***Level-1***	***Level-2***	***Level-3***
Pressure (MPa)	A	0.3792	0.4137	0.4482
Stand-off Distance (mm)	B	8	10	12
Nozzle Diameter (mm)	C	1.2	1.5	2.3
Fictitious	D	d_1	d_2	d_3

(b) Performance Indicators

S.N..	***Parameter Levels***				***Performance indicator***					
					Performance Indicators	*Performance Indicators*	*Performance Indicators*	*Performance Indicators*	Expected range	
	A	B	C	D					From	To
Material removal rate, *MRR* (g/min)										
1	1	1	1	1	0.1052	0.0836	20.6	0.1052	0.0456	0.1052
2	1	2	2	2	0.1364	0.1201	12.0	0.1364	0.0821	0.1417
3	1	3	3	3	0.125	0.1630	-30.4	0.125	0.125	0.1846
4	2	1	2	3	0.0909	0.1289	-41.8	0.0909	0.0909	0.1505
5	2	2	3	1	0.25	0.2284	8.7	0.25	0.1922	0.2518
6	2	3	1	2	0.0476	0.0313	34.3	0.0476	0.0313	0.0529
7	3	1	3	2	0.2857	0.2694	5.7	0.2857	0.2332	0.2928
8	3	2	1	3	0.0909	0.1289	-41.8	0.0909	0.0909	0.1505
9	3	3	2	1	0.1304	0.1088	16.6	0.1304	0.0708	0.1304
Overcut, *OC* (mm)										
1	1	1	1	1	2.37	2.4011	-1.3	2.37	2.3700	2.4567
2	1	2	2	2	2.42	2.3644	2.3	2.42	2.3333	2.4200
3	1	3	3	3	2.11	2.1344	-1.2	2.11	2.1034	2.1901
4	2	1	2	3	2.02	2.0444	-1.2	2.02	2.0133	2.1000
5	2	2	3	1	1.92	1.9511	-1.6	1.92	1.9200	2.0067
6	2	3	1	2	2.52	2.4644	2.2	2.52	2.4333	2.5200
7	3	1	3	2	1.72	1.6644	3.2	1.72	1.6334	1.7201
8	3	2	1	3	2.29	2.3144	-1.1	2.29	2.2833	2.3700
9	3	3	2	1	2.11	2.1411	-1.5	2.11	2.1100	2.1967
Taper cut, *TC* (mm)										
1	1	1	1	1	0.79	0.9111	-15.3	0.79	0.7889	1.1433
2	1	2	2	2	1.15	0.9178	20.2	1.15	0.7956	1.1500
3	1	3	3	3	0.96	1.0711	-11.6	0.96	0.9490	1.3034
4	2	1	2	3	0.66	0.7711	-16.8	0.66	0.6489	1.0033
5	2	2	3	1	0.77	0.8911	-15.7	0.77	0.7689	1.1233
6	2	3	1	2	1.45	1.2178	16.0	1.45	1.0956	1.4500
7	3	1	3	2	0.78	0.5478	29.8	0.780	0.4256	0.7800
8	3	2	1	3	0.73	0.8411	-15.2	0.73	0.7189	1.0733
9	3	3	2	1	0.76	0.8811	-15.9	0.76	0.7590	1.1134
*inclusion of fictitious parameter; **RE=Relative Error										

Table 2. ANOVA for *MRR*, *OC* and *TC*

Parameters	**Mean values**			**Final Mean**	**Sum of Squares**	**% Contribution**
	1st	*2nd*	*3rd*			
Material removal rate, MRR (g/min)						
A	0.1222	0.1295	**0.169**	0.1402	0.0038	7.9
B	**0.1606**	0.1591	0.101	0.1402	0.0069	14.4
C	0.0812	0.1192	**0.222**	0.1402	0.0310	64.2
D	0.1619	0.1566	0.1023	0.1402	0.0065	13.5
Over cut, OC (mm)						
A	2.3	2.1533	**2.04**	2.1644	0.1019	19.1
B	**2.0367**	2.21	2.2467	2.1644	0.0754	14.1
C	2.3933	2.1833	**1.9167**	2.1644	0.3424	64.1
D	2.1333	2.22	2.14	2.1644	0.0139	2.6
Taper cut, TC (mm)						
A	0.9667	0.96	**0.7567**	0.8944	0.0855	16.5
B	**0.7433**	0.8833	1.0567	0.8944	0.1478	28.5
C	0.99	0.8567	**0.8367**	0.8944	0.0417	8.1
D	0.7733	1.1267	0.7833	0.8944	0.2428	46.9

$$\hat{\Theta} = \Theta_{gm} + \sum_{i=1}^{n_{PV}} \left(\Theta_i - \Theta_{gm}\right) \qquad (2)$$

Here, $\hat{\Theta}$ represents the estimated value of the PI, Θ_{gm} is the grand mean of the test runs, Θ_i is the mean value corresponding to the process parameter at the specified level, and n_{PV} is the number of process variables. When considering only the 3 Abrasive Jet Machining (AJM) parameters (i.e., n_{PV}=3), a noticeable discrepancy is observed in the estimates of PIs in Table 1(a). Introducing the fictitious parameter (i.e., n_{PV}=4), the estimates of PIs using the additive law (2) in Table 1(b) closely match the test results [7].

To pursue a simple and reliable multi-objective optimization approach [26, 27], similar to the aforementioned concept, positive weighing factors ω_1,ω_2 and ω_3 (which satisfy ω_1+ω_2+ ω_3 = 1) are introduced. This leads to the formulation of a single function to optimize Material Removal Rate (MRR), Overcut (OC), and Taper Cut (TC) in the following form:

$$\Phi = \omega_1 \left(\frac{\mathrm{MRR_{max}}}{\mathrm{MRR}} - 1\right) + \omega_2 \frac{\mathrm{OC}}{\mathrm{OC_{max}}} + \omega_3 \frac{\mathrm{TC}}{\mathrm{TC_{max}}} \qquad (3)$$

Minimization of Φ provides the maximum MRR, minimum OC and minimum TC for the set of AJM process parameters. To achieve common optimum AJM process conditions equal weighing factors assigned are: ω_1=ω_2= $\omega_3 = \frac{1}{3}$. Table 3 gives the generated values of Φ. From equation (3) for each test run ANOVA is performed on Φ in Table 4 for 9 test runs and obtained optimum AJM parameters to achieve minimum Φ are: $A_3B_1C_3$ (Abrasive pressure, A= 0.4482 MPa; stand-off distance, B= 8 mm; and nozzle diameter, C= 2.3 mm). It is noted from the test run-7 of Table 1 corresponding to the identified optimum AJM process parameters.

The empirical relations developed for the MRR, OC and TC in terms of abrasive pressure (A), stand-off distance (B) and nozzle diameter (C) are:

$$MRR = 0.1593 + 0.0234\xi_1 + 0.0161\xi_1^2 - 0.0298\xi_2 - 0.0283\xi_2^2 + 0.0704\xi_3 + 0.0005\xi_3^2 \qquad (4)$$

$$OC = 2.0887 - 0.13\xi_1 + 0.0167\xi_1^2 + 0.105\xi_2 - 0.0683\xi_2^2 - 0.2383\xi_3 + 0.1008\xi_3^2 \qquad (5)$$

$$TC = 0.8525 - 0.105\xi_1 - 0.0983\xi_1^2 + 0.1567\xi_2 + 0.0167\xi_2^2 - 0.0767\xi_3 + 0.1153\xi_3^2 \qquad (6)$$

Here $\xi_1 = \frac{2000}{69}(A - 0.4137)$; $\xi_2 = \frac{1}{2}(B - 10)$; and $\xi_3 = \frac{1}{11}(20C - 35)$.

Table 3. Objective function Φ for the performance indicators of Table 1.

Test Run	Parameter Levels				Non-dimensional performance indicators			Φ (Eq.3)
	A	***B***	***C***	***D***	$\frac{MRR_{max}}{MRR} - 1$	$\frac{OC}{OC_{max}}$	$\frac{TC}{TC_{max}}$	
1	1	1	1	1	1.7250	0.8887	0.5423	1.0520
2	1	2	2	2	1.1017	0.9075	0.7895	0.9329
3	1	3	3	3	1.2933	0.7912	0.6590	0.9145
4	2	1	2	3	2.1536	0.7575	0.4531	1.1214
5	2	2	3	1	0.1467	0.72	0.5286	0.4651
6	2	3	1	2	5.0224	0.945	0.9954	2.3209
7	3	1	3	2	0.0034	0.645	0.5355	0.3946
8	3	2	1	3	2.1536	0.8587	0.5011	1.1712
9	3	3	2	1	1.1984	0.7912	0.5217	0.8371

Table 4. ANOVA results on Φ

Parameter	1-mean	2-mean	3-mean
A	0.9665	1.3025	**0.8010**
B	**0.85602**	0.8564	1.3575
C	1.51472	0.9638	**0.5914**

Equations (4)-(6) present the outcomes of additive law equations devoid of fictitious parameters. Corrections must be applied to these equations based on the deviation between the lowest and highest mean values of the output response and the respective grand mean value. Specifically, corrections for equation (4) encompass -0.03797 and 0.021633 for lower and upper bound values of MRR, while equation (5) involves corrections of -0.03111 and 0.055556 for lower and upper bound values of OC. Equation (6) sees corrections of -0.12111 and 0.232222 for lower and upper bound values of TC.

By employing the additive law (2), the performance indicators for the full factorial design of 27 experiments with the sequence of AJM parameters ((((A_i, B_j, C_k), k=1 to 3), j=1 to 3), i=1 to 3) are calculated from the ANOVA Table 2. Utilizing equations (4) to (6), MRR, OC, and TC values are generated for each set of AJM parameters. Figures 2–4 depict a favorable comparison between the estimates of performance indicators using additive law (2) and empirical relations (4) to (6). Notably, test data [7] for the optimal AJM parameters $A_3B_1C_3$ in Table 5 fall within the estimated range of MRR, OC, and TC.

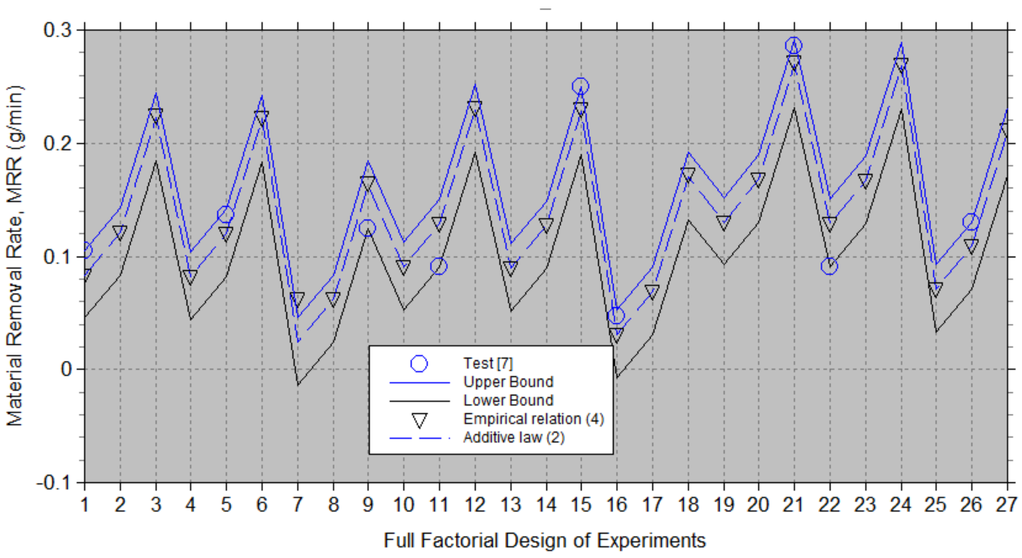

Figure 2. Design of Experiment of MRR.

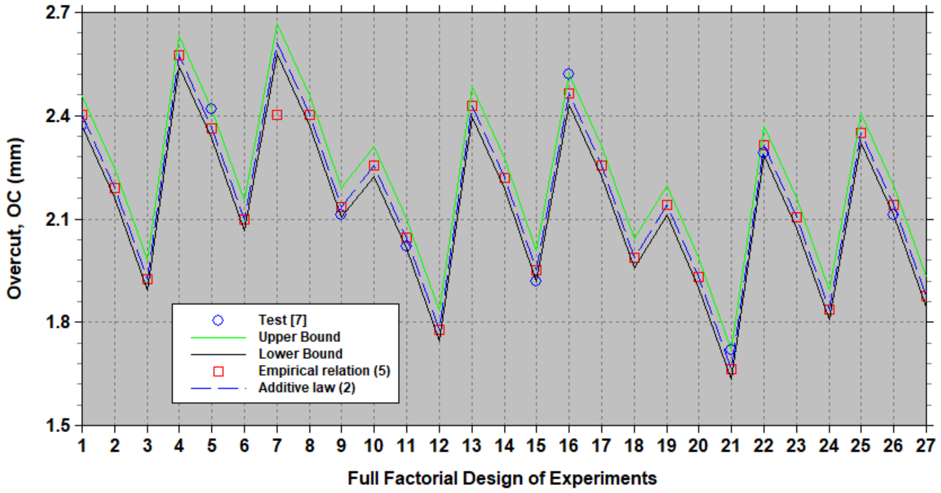

Figure 3. Design of Experiment of Overcut.

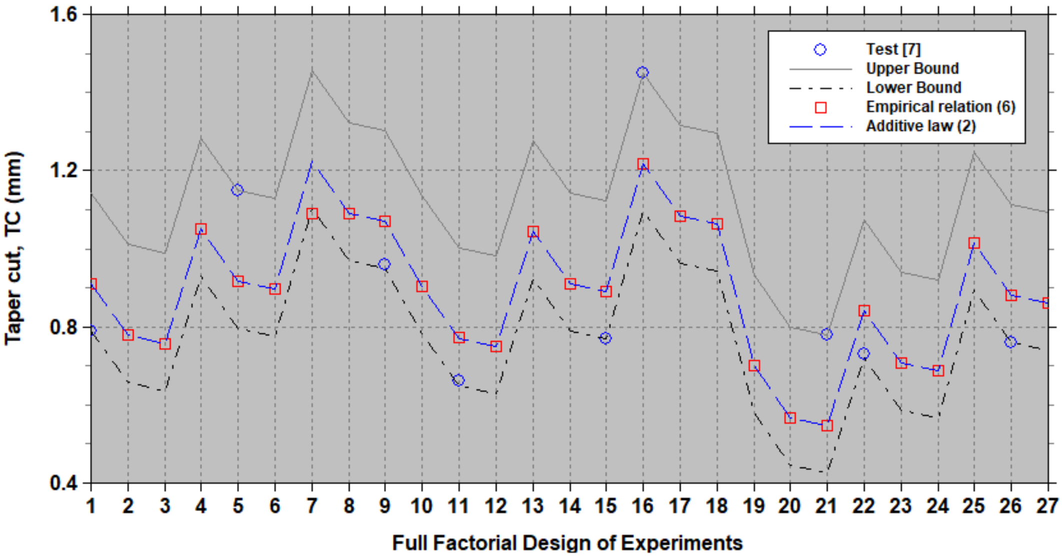

Figure 4. Design of Experiment of Taper cut.

Table 5. Estimates of the PIs (*MRR*, *OC* and TC) and test data to confirm the optimal AJM parameters (abrasive pressure, $A_3 = 0.4482$ MPa; stand-off-distance, $B_1 = 8$ mm; and nozzle diameter, $C_3 = 2.3$ mm)

Method of Evaluation	Material removal rate, *MRR* (g/min)	Overcut, *OC* (mm)	Taper cut, *TC* (mm)
Additive law (2) $n_p = 3$	0.2694	1.6644	0.5478
Empirical relation	0.2712	1.6646	0.5478
Expected range	0.2314 – 0.2910	1.6333–1.7200	0.4267–0.7800
Test [7]	0.2857	1.72	0.78

CONCLUDING REMARKS

In summary, abrasive jet machining (AJM) emerges as a viable option for GFRP. This study focuses on optimizing the AJM process parameters to achieve maximum MRR (material removal rate), overcut (OC), and taper cut (TC) for GFRP, utilizing a modified Taguchi approach. The results of multi-objective optimization reveal that the optimal AJM process variables for GFRP are abrasive pressure ($A_3 = 0.4482$ MPa), stand-off distance ($B_1 = 8$ mm), and nozzle diameter ($C_3 = 2.3$ mm). The introduction of a fictitious parameter ensures that the test results fall within the expected range of MRR, OC, and TC. The empirical relations developed in this work are valuable for estimating performance indicators (PIs) based on the specified AJM process variables. This paper advocates the application of the adapted Taguchi method to determine optimal variables for the AJM process, involving the representation of distinct quality attributes relative to a single response characteristic through non-dimensioning. The multi-responses optimization approach employed in this study is both straightforward and manageable, making it accessible with common calculators.

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