MATHEMATICAL MODEL AND OPTIMIZED PARAMETERS DESIGN IN AWJ MACHINING OF AIRCRAFT GRADE KEVLAR-EPOXY COMPOSITES

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ABSTRACT

Abrasive water jet (AWJ) is particularly useful for difficult-to-cut materials such as composites and ceramics in the recent past. However, proper and optimum cutting parameter selection is necessary for economic and efficient cutting with AWJ. In the present work, four important process parameters namely water jet pressure, abrasive flow rate, quality level and standoff distance were used to study their influence on kerf quality characteristics, namely, surface roughness and top kerf width during AWJ cutting of Kevlar-epoxy composites. The optimal setting of cutting parameters was determined using Taguchi's robust design method. It is observed that the quality level and water jet pressure have more significant effect on surface roughness and top kerf width rather than abrasive flow rate and standoff distance.

Keywords: Abrasive Water Jet Cutting, Kevlar Composite,, Surface Roughness, Top Kerf Width, Taguchi Method

I. INTRODUCTION

Abrasive water jet machining (AWJM) is an advanced machining process widely used for machining of difficult-to-cut materials such as composites, Ti alloys, silica Kevlar, rocks and ceramics. The main advantages of this process include no thermal distortion, minimal residual stresses on the work piece, no burr formation, no delamination and flexible to cut any material [1, 2]. In AWJM, material removal occurs due to erosion caused by the impact of abrasive particles on the work surface. A stream of small abrasive particles is entrained in the pressurized water jet such that the water jet's momentum is partly transferred to the abrasive particles. Water is used as a carrier fluid to accelerate the abrasive particles to produce a highly coherent AWJ, which is focused on the work piece surface through a nozzle [3, 4]. A schematic of the AWJC process is shown in Fig. 1.

II. LITERATURE REVIEW

Various researches have been carried out to investigate the influence of process parameters on the cutting quality of AWJC process. Studies by [5] on cutting of FRPs observed that the cut surface quality is dependent upon process parameters such as water jet pressure (WJP), feed rate, nozzle diameter, standoff distance (SOD) and material thickness. Singh et al. [6] experimentally studied the AWJ cut surface finish for different materials (aluminium, steel, Kevlar and rubber). It was found that better surface finish is obtained on the top part of the cut surface at lower WJP and by increasing abrasive flow rate (AFR) and decreasing traverse speed (TS). Ramulu and Arola experimentally investigated the influence of cutting parameters on the surface roughness (R_a) and top kerf width (TKW) in AWJC of graphite/epoxy laminates. It was concluded that grit size and SOD have the most significant influence on R_a at low cutting depth, and grit size and TS were the most significant parameters within the deformation wear zone at higher cutting depth [7]. Wang and Guol developed a semi-empirical model for predicting the depth of jet penetration in AWJC of polymer composites.

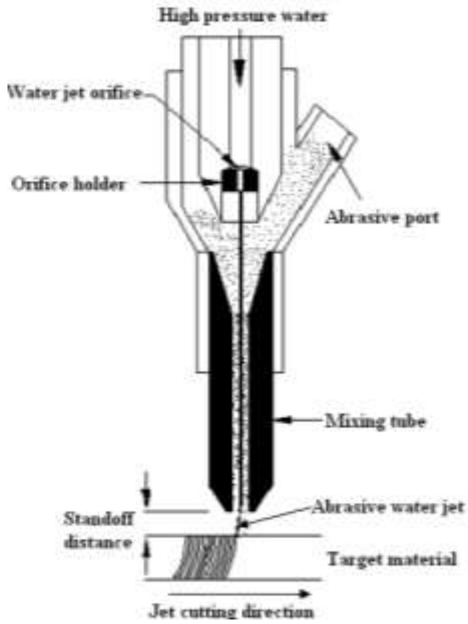


Fig.1. Schematic Diagram of Abrasive Water Jet Cutting

They concluded that the proper prediction of the depth of penetration is important to achieve through cuts and to eliminate delamination [8]. Chen et al. investigated the kerf characteristics of thick alumina ceramics using AWJC. It was found that WJP, TS and SOD have a greater effect on TKW than AFR. TKW was found to increase with an increase in TS [9].Wang studied the machinability of polymer matrix composites using AWJ. It was found that TKW, BKW and kerf taper increased with WJP and SOD though a smaller rate of increase of BKW associated with SOD was observed. TS had a negative effect on both TKW and BKW and a slight decrease in kerf taper was found with increase in TS [10]. Lemma et al. experimentally studied the AWJC of Kevlar fiber reinforced polymer with head oscillation technique. A significant improvement in the surface finish was obtained by head oscillation technique than normal AWJC [11]. Conner et al. investigated the AWJM of thin aerospace structural metal alloys (Inconel, titanium and aluminum alloy). It was found that increasing the traverse rate for a fixed WJP, garnet abrasive size, and AFR increases R_a. BKW decreases with an increase in TS, however, the rate of decrease becomes less by increasing AFR [12]. Siddiqui and Shukla investigated the influence of three process parameters (water jet pressure, abrasive flow rate and quality level) on surface roughness in AWJC of Kevlar composites. The optimal parameter setting was determined using a hybrid Taguchi and response surface method. The experimental results and ANOVA analysis indicate that quality level and water jet pressure have more significant effect on Ra. A second order response surface model was also developed using the central composite rotatable design [13]. Azmir and Ahsan assessed the influence of AWJM process parameters on R_a of Kevlar fiber reinforced epoxy composites. It was found that WJP, SOD, TS and type of abrasive were the significant control factors and cutting orientation was an insignificant factor in controlling R_a [14]. A Design of experiments approach was used considering variables such as water pressure, stand-off distance, traverse speed, orifice diameter and abrasive flow rate. It was observed that water pressure, nozzle diameter have important role in controlling the depth of cut [15]. In this paper, behavior of a machinability model/index for composite cutting was studied [16]. Taguchi's method based experiments were carried out to study the effect of different process variables on kerf taper and kerf width. It was found that nozzle traverse speed was the most significant factor affecting the top kerf width and taper angle [17].

III. PROBLEM DESCRIPTION

1. From the literature review, it can be concluded from the best of knowledge of author that no research work has been reported so far on AWJC process of difficult-to-cut aircraft grade Kevlar-epoxy composites using Taguchi's robust design methodology.
2. In this paper, the Taguchi method has been applied to optimize kerf quality characteristics namely surface roughness (R_a) and top kerf width (TKW) in AWJC process of Kevlar-epoxy composites.
3. Determination of optimal cutting parameters for producing the better surface quality and their relative rankings is obtained by the signal-to-noise ratio and analysis of variance response.
4. Multilinear regression models will also be developed for the prediction of R_a and TKW.

IV. EXPERIMENTAL METHOD

4.1 Taguchi's Robust Design Method

Taguchi method is an important tool for robust process design and has been widely used in engineering analysis to optimize design for performance, quality and cost. Taguchi method is also strong tool for the design of high quality systems by a simple, systematic, and effective approach. Taguchi method defines the process/product quality, in terms of the quality loss function or mean square deviation in the functional characteristic of a process/product from the desired value. The uncontrollable external factors which cause these functional deviations are called noise factors such as machine vibrations, temperature, humidity and human factors etc. Taguchi suggested that it is better to make the process robust rather than machinery (which is costly one) just by nullifying the effects of variations through the proper selection of process parameter settings.

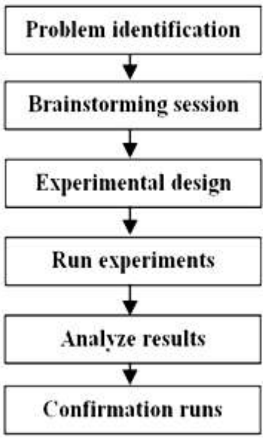


Fig.2. Flow Chart of Taguchi Method

4.2 Selection of Taguchi Orthogonal Array for Matrix Experimentation

Taguchi method [Fig. 2] uses a matrix of experiments called Taguchi orthogonal array (TOA), to efficiently study the simultaneous effect of several process parameters on the responses. According to the Taguchi method concept, the selection of a TOA depends on the total degree of freedom (*dof*) of the process [18]. The total *dof* is computed as:

dof = ((number of levels-1) for each parameter + (number of levels-1) for each interaction +1)

In the present case, *dof* = (3-1)$\times$4 +1 = 9 (with no interaction effect). Hence, $L_9(3^4)$ TOA is selected for carrying out the experimental work as shown in Table 2.

4.3 Computation of Signal-To-Noise Ratio

Taguchi method recommends signal-to-noise (S/N) ratio as the objective function for matrix experiments. Here, the 'signal' represents the desirable value and the 'noise' represents the undesirable value and S/N ratio expresses the scatter of quality characteristics from the desired value. The larger S/N ratio will be an indication of better quality characteristics and less scatter from the desired value. Generally, there are three categories of quality characteristic for S/N ratio, i.e. smaller-the-better, larger-the-better and nominal-the-better. In the present experimental design, the smaller-the-better quality characteristic is used for both R_a and TKW as we intend to minimize both of them. The S/N ratio (η_i) is computed as:

$$\eta_i = -10\log10(\text{MSD}) \qquad (1)$$

where MSD is the mean square deviation or quality loss function for each quality characteristic. The MSD for smaller-the-better quality characteristic is computed as:

$$\text{MSD}=\frac{1}{n}\left(\sum_{j=1}^{n} y_{ij}{}^{2}\right) \qquad (2)$$

where y_{ij} is the value of *i*th response for *j*th experimental run and *n* is the total number of experimental runs.

4.4 Analysis of Variance

Analysis of variance (ANOVA) is a computational technique used to find out the relative effect of different factors by the decomposition of their variances. The sum of squares (SS) and mean sum of squares (MS) and pooled error is computed (by pooling the insignificant factors A and B) to find out the F ratio and percentage contribution (PC) [19]. The degree of freedom (df) for each factor is calculated as:

df = number of level - 1

V. EXPERIMENT EXECUTION PHASE

5.1 Samples Fabrication

In the present work, 2 mm thick, $[0^o]_8$ laminates have been prepared by the standard autoclave vacuum bagging process using bidirectional woven Kevlar-epoxy prepregs (Fiber volume fraction-0.37) supplied by Hexcel Composites. Consistent quality of sample coupons was ensured by conducting void fraction, inter-laminar shear strength and 3-point flexural tests [Fig. 3]. The Tensile strength, shear modulus and maximum working temperature of Kevlar specimen are 65.5 MPa, 4.0 GPa and 150°C respectively. The application of this material is in impact resistant structural components of Dornier transport aircraft.

Fig.3. AWJ Cut Thin Kevlar-Epoxy Speciman

5.2 Experimental Setup and Procedure

20 mm long, single pass, through cuts in a square shape were cut on test specimens using the OMAX 2652® Machining Centre (of 400 MPa pump capacity) [Fig. 4]. The orifice and mixing tube diameters are kept constant at 0.33 mm and 0.762 mm, respectively. All experiments are conducted using garnet as the abrasive with mesh size # 80. This size is selected due to its wide spread use in industrial applications of AWJC. Four process parameters namely water jet pressure, abrasive flow rate, quality level and standoff distance each at three levels were used as shown in Table 1. The initial setting of parameters was: Water jet pressure–250 MPa, Abrasive flow rate–250 g/min, Quality level–3, and Standoff distance–1 mm as per the TOA settings. The dimensionless cutting quality level is defined by the mean R_a of the upper, middle and lower zones of the AWJ cut surface as captured by Scanning electron microscope (SEM) images in Fig. 5 and is a qualitative measure to obtain the appropriate traverse speeds [20]. Higher the quality level, lower will be the traverse speed.

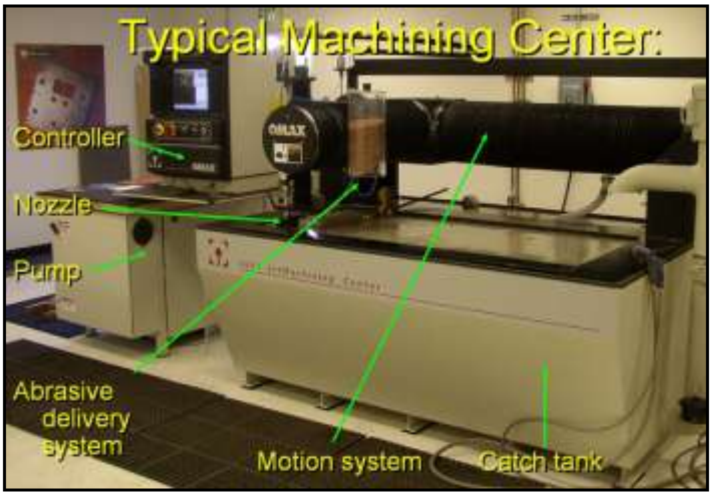
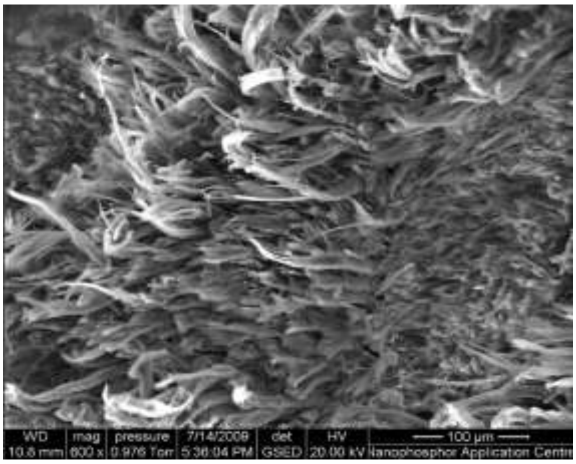


Fig.4. OMAX AWJ Machine Setup

The R_a profile was measured at the top and bottom surface of specimen using a 'Stylus profilometer' (Taylor-Hobson subtronic 10) to avoid the striation effect at entry and exit of the jet. The measurements were repeated thrice and their average values used. The TKW was measured using a Tool Maker's Microscope at 20X magnification. The KW taken is the average of four measurements of each cut. The average measured values of R_a and TKW are shown in Table 3.



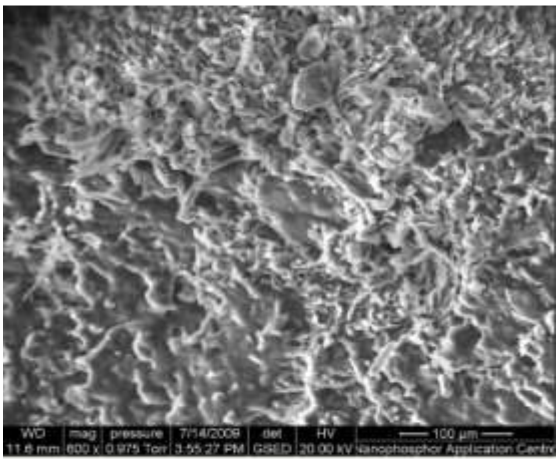


Fig.5. SEM Images of AWJ Cut Surfaces Obtained at Parameter Quality Levels (A) 3 and (B) 5

Table1. Process Control Factors and Their Levels

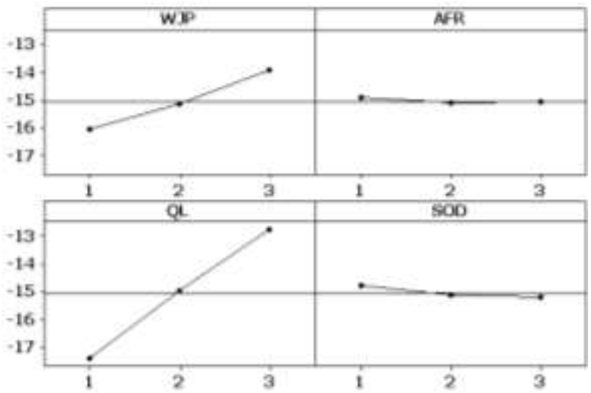
Factor	Symbol	Units	Low	Medium	High
Water jet pressure	A	MPa	250	300	350
Abrasive flow rate	B	g/min	250	325	400
Quality level	C	--	3	4	5
Standoff distance	D	mm	1	2	3

Table 2. L_9 Orthogonal Array

Exp. No.	WJP	AFR	QL	SOD
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table3. Experimental Observations and Computed S/N Ratio for R_a and TKW

Exp. No.	R_a (µm)	TKW (mm)	S/N ratio	S/N ratio
1	8.0	0.99	-18.17	0.087
2	6.4	1.10	-16.26	-0.828
3	5.0	1.30	-13.80	-2.279
4	5.7	1.21	-15.41	-1.656
5	4.3	1.25	-12.87	-1.938
6	7.6	1.15	-17.50	-1.214
7	3.8	1.40	-11.82	-2.923
8	6.7	1.20	-16.52	-1.584
9	4.8	1.28	-14.15	-2.144
Mean	5.81	1.21	-15.17	-1.609



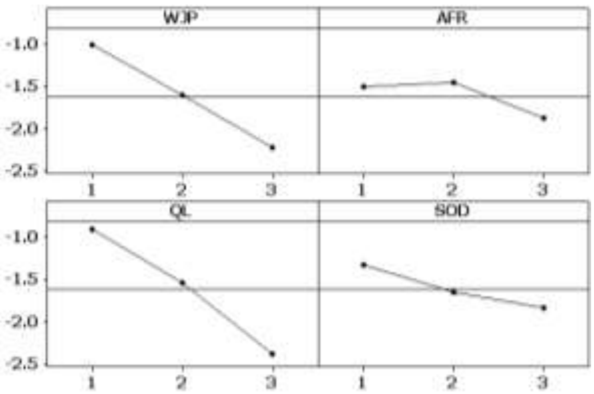


Fig.6. Response Plot S/N Ratio for R_a **Fig.7. Response Plot S/N Ratio for TKW**

Factor	SS	df	MS	F	PC (%)
Water jet pressure	6.920	2	3.460	39.772	17.257
Abrasive flow rate	0.055*	2	0.028	---	0.138
Quality level	32.490	2	16.243	186.700	81.008
Standoff distance	0.293*	2	0.146	1.682	0.729
Pooled error	0.348	4	0.087		

* Pooled factors

Table 4. ANOVA Response for R_a

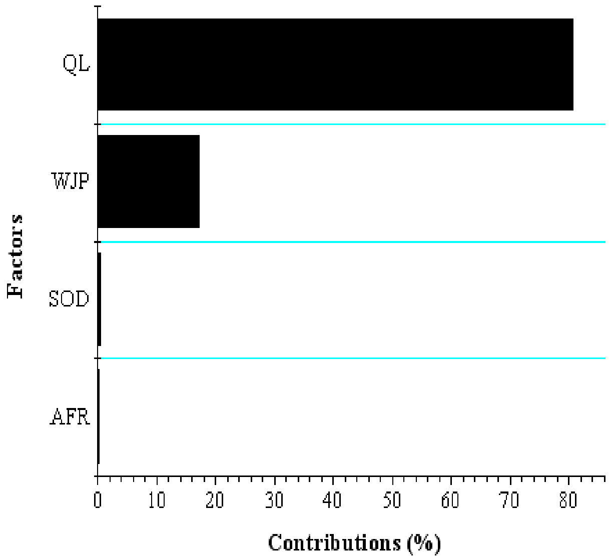


Fig.8. Percentage Contribution of Different Factors for R_a

Factor	SS	df	MS	F	PC (%)
Water jet pressure	2.198	2	1.099	6.033	31.646
Abrasive flow rate	0.332#	2	0.166	---	4.785
Quality level	3.289	2	1.645	9.030	47.372
Standoff distance	0.396#	2	0.198	1.088	5.706
Pooled error	0.729	4	0.182		

Pooled factors

Table 5. ANOVA Response for TKW

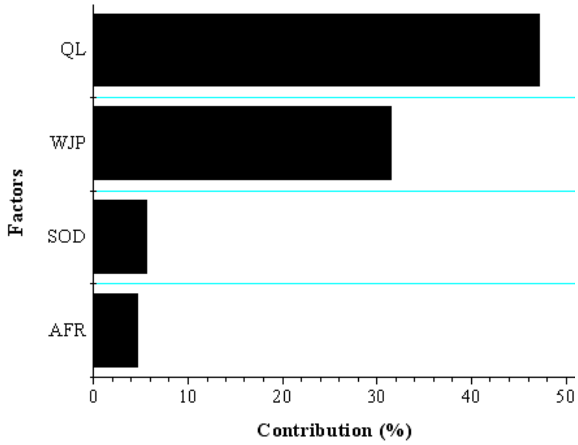


Fig.9. Percentage Contribution of Different Factors for tkw

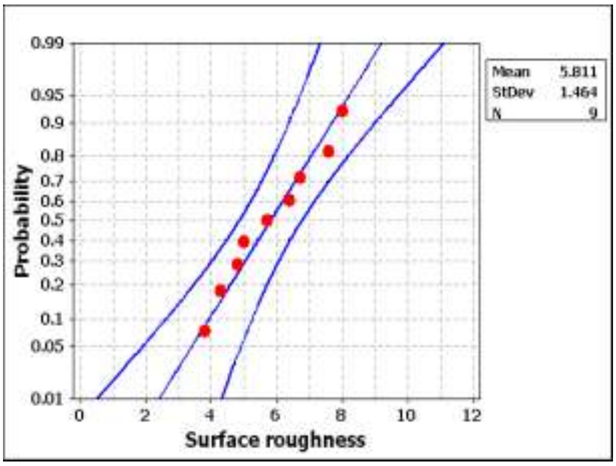


Fig.10. Normal Probability Plot of r_a

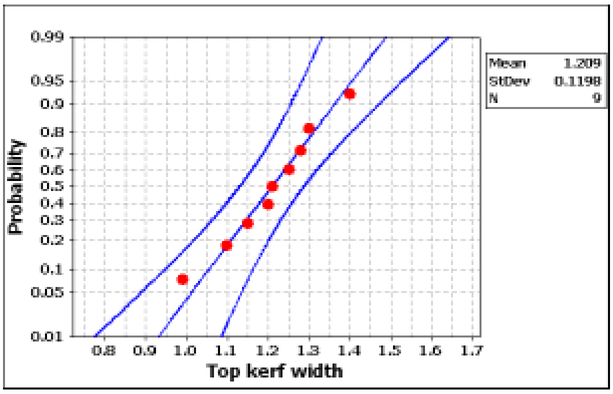


Fig.11. Normal Probability Plot of tkw

VI MATHEMATICAL MODEL

The correlation between factors (WJP, AFR, QL and SOD) and R_a and TKW in AWJC of Kevlar-epoxy composites obtained by certain mathematical models and expressed as follows:

$$R_a = 16.0 - 0.0137\times WJP - 0.00022\times AFR - 1.53\times QL + 0.0500\times SOD \quad (3)$$

$$TKW = 0.155 + 0.00163\times WJP + 0.000289\times AFR + \ 0.102\times QL + 0.0317\times SOD \quad (4)$$

The values of coefficients of correlation R^2 (adj) obtained from Eqs. (3) and (4) are 0.974 and 0.930, respectively which are considerably high values. Normality test is also conducted to establish the goodness of fit of regression models. Normality distribution test (for 95% CI) for both the regression models is carried out with the help of a normal probability plot (NPP) to see the distribution of residual error. Under perfect normality, the plot will be a 45 degree line. The NPP plots (Figs. 10 and 11) obtained from the empirical models of R_a and TKW show that the lines are close to the 45 degree line.

VII. RESULTS AND DISCUSSION

The computed S/N ratios for R_a and TKW are shown in Table 3. Taguchi analysis observes the higher value of mean S/N ratio as better quality characteristic. The factor levels corresponding to maximum average S/N ratio are selected as optimum level. The optimum level represents the combination of control factor levels that is expected to produce the best performance. The response graph of factor levels for R_a and TKW are shown in Figs. 6 and 7, respectively. The maximum average S/N ratio for minimum R_a is obtained at level 3 (350 MPa) of WJP, level 1 (250 g/min) of AFR, level 3 (5) of QL and level 1 (1 mm) of SOD i.e. the optimum parameter settings for minimum R_a is $A_3B_1C_3D_1$ (Fig. 6) that means higher water jet pressure and quality level (higher kinetic energy and less deflection of the jet) is desirable for better surface finish. The obtained parameter settings are in line with the earlier findings [7, 14].

The maximum average S/N ratio for minimum TKW is obtained at level 1 (250 MPa) of WJP, level 2 (325 g/min) of AFR, level 1 (3) of QL and level 1 (1 mm) of SOD i.e., the optimum parameter settings for minimum TKW is $A_1B_2C_1D_1$ (Fig. 7) that means lower water jet pressure, quality level and lower standoff distance (lower kinetic energy of jet, higher traverse speed and less divergence of water jet at the top) is required for minimum TKW. The observed parameters settings are similar to the findings of [9, 10]. The ANOVA response for R_a and TKW are given in Table 4 and 5, respectively. The quality level and water jet pressure has more significant effect on R_a and TKW rather than abrasive flow rate and standoff distance. Figs. 8 and 9 illustrate the percentage contributions of different factors in descending order as Quality level (81.0%), water jet pressure (17.26%), standoff distance (0.729%) and abrasive flow rate (0.138%), respectively, for R_a while Quality level (47.37%), water jet pressure (31.65%), standoff distance (5.71%) and abrasive flow rate (4.79%), respectively, for kerf taper.

VIII. FURTHER RESEARCH SCOPE

1. Experimental study can also be extended for thicker composite samples.
2. Optimization of multiple performance characteristics is to be studied and can be compared with the results of single objective optimization.
3. Interaction effect of different parameters on the performance characteristics can also be studied and non-linear models will be developed further for the prediction of tailored surface integrity in AWJC process of polymer composites.
4. Studies on delamination of Kevlar fiber laminates are to be investigated in the future.

IX. CONCLUSION

The following conclusions can be drawn from the results of the present work

1. The use of Taguchi's robust design method to optimize the AWJC process with the kerf quality characteristics, namely, surface roughness and top kerf width has been reported in this paper.

2. The quality level and water jet pressure has more significant effect on kerf quality characteristics rather than abrasive flow rate and standoff distance.
3. Higher water jet pressure and quality level with lower abrasive flow rate and standoff distance is desirable for better surface finish.
4. Lower water jet pressure, quality level, standoff distance and moderate value of abrasive flow rate is required for minimum top kerf width.
5. The developed regression models successfully predicted the surface roughness and kerf width of AWJ cut Kevlar-epoxy composites within the range of cutting parameters and can be used for the determination of optimal cutting parameters for producing a better cut surface quality.

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