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Paper

COMPARATIVE INVESTIGATION OF ABRASIVE WATERJET CUT KERF QUALITY CHARACTERISTICS FOR ARAMID, GLASS AND CARBON FIBER REINFORCED COMPOSITES USED IN TRANSPORT AIRCRAFT APPLICATIONS

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ABSTRACT

Water jet technology, is now a days increasingly being used in a variety of applications including mining, process, medical and for machining of difficult-to-cut materials like composites, super alloys, rocks and ceramics. In AWJ cutting of fiber reinforced composites (FRCs), the kerf quality and finish produced are usually poor, necessitating finishing operations leading to further delamination. This paper presents a comparative study of the effect of three major process parameters namely water jet pressure (WJP), abrasive flow rate (AFR) and quality level (QL), on two kerf quality characteristics (KQCs) namely surface roughness (R_a) and kerf taper (K_t) in AWJ cutting of three different grades (aramid, glass and carbon) of bi-directional epoxy composite laminates fabricated from prepregs. This grade of composites is used in the Dornier transport aircraft program. Robust parameter design in AWJ cutting of above FRCs using the Taguchi method (TM) is presented. Three levels of process parameters were used to study their influence on R_a and K_t and find their optimum selection using a $L_{27}(3^3)$ Taguchi orthogonal array. It was found that higher level of WJP and QL and lower level of AFR are desirable for producing maximum surface finish and minimum kerf taper.

1 INTRODUCTION AND LITERATURE REVIEW

FRCs have attracted increasing attention for use as load-bearing and impact resistant components, particularly in the aerospace and automobile industries. These materials have numerous outstanding properties, such as high specific strength, high specific modulus of elasticity, light in weight, improved corrosion resistance, etc. The material removal in FRCs may be totally different due to their non-homogeneity, anisotropy and the abrasive characteristics unlike metallic materials (Davim et al., 2004). Therefore, cutting of FRCs requires an in depth understanding of the behavior of different process parameters to achieve desired accuracy and efficiency. It helps to realize finished products with specified dimensions, surface finish and tolerances. Conventional machining processes require direct contact between the cutting tool and the part to be machined. The quality of the machined part and tool wear are two major concerns in these machining processes. The application of conventional metal cutting tools in FRCs leads to severe problems such as fiber damage, delamination and matrix-cracking which ultimately result in poor cut surface quality.

There are several advanced machining processes which avoid direct contact between the machine and the work piece, thereby eliminating problems of tool wear and improving the quality of the machined component. Abrasive water jet machining (AWJM) is one of the useful advanced machining process for machining FRCs unlike laser beam machining suffers from the problem of heat-affected zones which resulted in large burr formation (Shanmugam et al., 2002). AWJM is a contact less machining process, induces no thermal distortion, minimal residual stresses on the work piece, minimum fiber damage, delamination and cracking, narrow kerf width, and is less sensitive to material properties (Chen et al., 1996; Jain and Jain, 2001). 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 (Momber and Kovacevic, 1998). A schematic diagram of an AWJM process is shown in Fig. 1.

(Hashish, 1991) studied the effects of AWJ parameters on surface texture and kerf taper on thin metal sheets. Abrasive particle size was found to be the dominant parameter affecting the surface finish. Some minor work hardening may also resulted which can be totally eliminated under certain jet and traverse speed conditions. (Chen et al., 1996) investigated the kerf characteristics of alumina ceramics and (Wang and Liu, 2006) explored the profile cutting on alumina ceramics by using AWJC. It was found that water jet pressure, traverse speed and standoff distance have a greater effect on kerf taper than abrasive flow rate. Kerf taper was found to increase with an increase in traverse speed. (Wang, 1999) experimentally studied the machinability of polymer composites using AWJ. It was found that top and bottom kerf width and kerf taper increased with water jet pressure and standoff distance though a smaller rate of increase of bottom kerf width associated with standoff distance was observed. Traverse speed had a negative effect on both top and bottom kerf width and a slight decrease in kerf taper were found with increase in traverse speed.

(Rahmah et al., 2003) experimentally studied the AWJM of Kevlar/phenolic composites. It was found that abrasive flow rate has least significant effect on surface roughness and kerf taper while surface roughness is affected by jet penetration depth and its interaction with supply pressure, standoff distance and traverse speed. (Patel and Chen, 2003) experimentally studied the AWJ cutting by nozzle oscillation technique. A comparison study was also conducted using different surface texture parameters between a straight and oscillation cut methods. A significant improvement was obtained in cut surface quality by nozzle oscillation technique in comparison to straight cut. (Ramulu et al., 2005) during investigation of the AWJ drilling models found that the water pressure, abrasive flow rate and drilling time significantly affected the dimensions and accuracy of the AWJ drilled holes.

(Feng et al., 2007) studied the machining performance of alumina ceramics by AWJ milling. It was found that the nozzle traverse speed and traverse feed have a significant effect on the cut surface quality. It was also noticed that the material removal rate and the milling depth would be increased at the higher water jet pressure and standoff distance. (Siddiqui et al., 2008) used a hybrid Taguchi and response surface method approach for optimization of surface finish in AWJM of Kevlar composites. It was found that quality level and water jet pressure were the more significant factors affecting R_a in comparison to abrasive flow rate. (Shanmugam et al., 2008) conducted an experimental study to minimise or eliminate the kerf taper in AWJ cutting of alumina ceramics by using a kerf-taper compensation technique. It was found that kerf taper compensation angle have the most significant effect on the kerf taper and the kerf taper angle varied almost linearly with the compensation angle. (Siddiqui et al., 2008) studied the optimization of surface finish in AWJ cutting of aircraft grade glass/epoxy composites. It was found that better surface was obtained at higher water jet pressure and quality level and lower abrasive flow rates. Small amount of ply delamination was observed at the entry and exit of the jet due to moisture entrapement.

This paper presents a comparative study performed to analyze the effect of the individual process parameters on KQCs for the three varieties of FRCs. The optimum setting of process parameters was determined applying the TM. The experimental results and analysis of variance indicate that quality level and water jet pressure have a more significant effect on the KQCs in comparison to abrasive flow rate. 3-D contour plots are also drawn among process parameters (WJP, AFR and QL) to study and analyze their interaction effect on R_a and K_t.

2 TAGUCHI ROBUST DESIGN

Design of experiment is a statistical approach for the simultaneous evaluation of two or more factors for their ability to affect the resultant average or variability of a particular process characteristic. The Taguchi technique is a methodology for finding the optimum setting of control factors to make the product or process insensitive to noise factors such as laminate thickness, environmental conditions and human errors (Phadke, 1989). The Taguchi technique uses a matrix of experiments called Taguchi orthogonal array (TOA), to efficiently study the simultaneous effect of several process parameters on the responses.

Taguchi suggested signal-to-noise (S/N) ratio as the objective function for matrix experiments. Taguchi classified objective functions into three categories namely smaller-the-better type, larger-the-better type and nominal-the-best type. The optimum level of factor is the level that results in the highest value of S/N ratio in the experimental design. In the present experimental design, the smaller-the-better quality characteristic is used for surface roughness (R_a) and kerf taper (K_t) as we intend to minimize both for obtaining a better cut surface quality. Therefore, the smaller-the-better quality characteristic S/N ratio (η) is used which is computed as follows:

$$\eta = -10\log_{10}(\text{MSD}) \tag{1}$$

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

$$\text{MSD} = \frac{1}{n}\left(\sum_{i=1}^{n} y_i^{\,2}\right) \tag{2}$$

where y_i is the value of *i*th experimental run and *n* is the total number of experimental runs. Twenty seven experimental runs are conducted according to the standard $L_{27}(3^{13})$ TOA. This TOA allows studying the main effects of three cutting parameters as well as their first order interactions. The main objective of the present work is to determine and compare the set of optimum process parameters for glass, Kevlar and carbon/epoxy composites which will lead to a better AWJ cut kerf quality characteristics such as R_a and K_t.

2.1 AWJC Experimental Setup and Procedure

The OMAX 2652® Machining Centre (400 MPa pump capacity) is used for carrying out AWJC process. 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 AWJM. 20 mm long through cuts in square shape are cut on the test specimen of thickness 2.5 mm in a single pass. In the present work, vacuum bagged and autoclave cured (at 130ºC temperature and 5 bar pressure), bidirectional aramid (Kevlar), glass and carbon-epoxy prepregs (of resin volume fraction equal to 0.50, 0.37 and 0.46 respectively) supplied by Hexcel Composites are used (Tambe 2005). These prepregs are widely used in the manufacturing of Dornier transport aircraft components. Three cutting parameters i.e. water jet pressure, abrasive flow rate and quality level, each at three levels (to account for curvature effect, if any) as shown in Table 1 are used. The cutting parameters and their levels selected are primarily based on AWJ machine constraints and literature review. The dimensionless cutting quality level (QL) is defined by the mean R_a of the upper, middle and lower zones of the AWJ cut surface. The R_a profile was measured using a 'Stylus profilometer' (Taylor-Hobson Surtronic 25 with diamond stylus of 5 µm tip radius and 0.01 µm resolution). The R_a was measured at the top and bottom surface of specimen to avoid the jet striation effect at entry and exit side. The measurements were repeated twice and their average values used. The top and bottom kerf widths were measured using a Tool Maker's Microscope at 20X magnification (wide field 10x eyepieces with built-in crosshair reticle). Both kerf widths taken are the average of five measurements for each cut, from which kerf taper or K_t (deg) is calculated as follows:

$$K_t \text{ (deg)} = [(Top\ kerf\ width - Bottom\ kerf\ width) \times 180/(2\pi \times Specimen\ thickness)] \quad (3)$$

A schematic of the kerf geometry of a through cut generated by AWJ is shown in Fig. 3. The measured average values of R_a and K_t as per the standard L_{27} TOA settings is shown in Table 2.

3 RESULTS AND DISCUSSION

Figures 2 and 3 below show the comparative effect of QL and WJP on R_a and K_t respectively, for glass-epoxy, Kevlar-epoxy and carbon-epoxy composites. It was found that R_a decreases with increase in QL (or low traverse speeds for all composites) and K_t decreases with increase in WJP (due to increase in kinetic energy and less deflection of AWJ).

Tables 3, 4 and 5 show the response table S/N ratio for surface roughness and kerf taper for glass-epoxy, Kevlar-epoxy and carbon-epoxy, respectively. It was found by averaging the S/N ratios at different levels of process parameters that higher level of water jet pressure (level 3), low level of abrasive flow rate (level 1) and higher level of quality (level 3) is required for optimum surface finish and minimum kerf taper. From a physical point of view of the AWJC process, higher water jet pressure increases the ability of material removal, leading to decrease in surface roughness and kerf taper due to increased kenetic energy AWJ. Lower abrasive flow rate decreases the interference between particles and increases the particle energy as well as the effectiveness of individual particle in cutting the material to yield a superior surface finish. Lower standoff distance produces a smoother surface due to increased jet kinetic energy. Higher quality level (lower traverse speed) allows more overlap cutting action and more number of abrasive particles to impinge the surface, thereby increasing the surface finish and decreasing the kerf taper (Momber and Kovacevic, 1998).

3.1 Multiple Regression Analysis

The correlation between process parameters (WJP, AFR and QL) and R_a and K_t in AWJC of glass, carbon and Kevlar/epoxy composites obtained by multiple linear regression assuming interaction effects to be negligibly small is expressed by the following equations -

$$R_{aG} = 16.0 - 0.0127(\text{WJP}) - 0.000897(\text{AFR}) - 1.52(\text{QL})\ (R^2 = \text{'}0.997\text{'}) \quad (4)$$

$$K_{tG} = 6.35 - 0.00306(\text{WJP}) - 0.00103(\text{AFR}) - 0.561(\text{QL})\ (R^2 = \text{'}0.905\text{'}) \quad (5)$$

$$R_{aC} = 11.3 - 0.0103(\text{WJP}) + 0.00300(\text{AFR}) - 0.583(\text{QL})\ (R^2 = \text{'}0.903\text{'}) \quad (6)$$

$$K_{tC} = 6.05 - 0.00740(\text{WJP}) - 0.00560(\text{AFR}) - 0.165(\text{QL})\ (R^2 = \text{'}0.845\text{'}) \quad (7)$$

$$R_{aK} = 14.3 - 0.0190(\text{WJP}) + 0.00633(\text{AFR}) - 1.00(\text{QL})\ (R^2 = \text{'}0.859\text{'}) \quad (8)$$

$$K_{tK} = 6.93 - 0.00410(\text{WJP}) - 0.00103\,(\text{AFR}) - 0.673(\text{QL})\ (R^2 = \text{'}0.846\text{'}) \quad (9)$$

where 'R' is the regression coefficient and actual value of WJP used is in MPa, AFR is in g/min and QL is a dimensionless quantity.

The value of coefficient of correlation (R^2) obtained from Eqs. 4 and 5 are 0.997 and 0.903 in case of glass/epoxy composite, 0.903 and 0.845 for carbon-epoxy composite (Eqs. 6 and 7) and 0.859 and 0.846 for Kevlar-epoxy composite (Eqs. 8 and 9), respectively which are considerably high values (near to the ideal value of 1 corresponding to the line of best fit).

Normality test is also conducted to establish the goodness of fit of regression model. Normality distribution test for R_a and K_t 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 (Figures 5, 6 and 7) obtained from the empirical models of R_a and K_t show that the line is very close to the 45 degree inclined line.

Figures 8, 9 and 10 show the 3-D contour plots drawn among the process parameters WJP, AFR and QL to study their interaction effect on R_a and K_t for all fiber composites. It was found that higher value of WJP and QL are desirable for optimum surface finish and minimum kerf taper (Figure 8). It was also observed that higher value of WJP and lower to moderate AFR is desirable for minimum R_a and K_t (Figure 9).

4 CONCLUSIONS

Based on the above Taguchi experimental analysis and results, the following conclusions can be drawn-

1. Water jet pressure and quality level are the most significant factors affecting surface roughness and kerf taper. Abrasive flow rate has the least effect on R_a and K_t among the three process parameters.
2. It is observed that higher level of water jet pressure (A_3) and quality level (C_3) and lower level of abrasive flow rate (B_1) are desirable for optimum surface finish and minimum kerf taper which is also confirmed by the 3-D contour plots drawn among the process parameters.
3. Same optimum parameter setting ($A_3B_1C_3$) is obtained for glass, Kevlar and carbon/epoxy composite samples in order to get minimum value of R_a and K_t.
4. It can be observed that as the quality level increases (at low traverse rate) R_a decreases whereas kerf taper decreases with increase in water jet pressure (due to increase in kinetic energy and less deflection of AWJ).
5. The developed regression models successfully predicted the R_a and K_t values of AWJ cut glass, Kevlar and carbon/epoxy composites within the chosen range of cutting parameters. These can be used for the determination of optimal process parameters for producing a better AWJ cut surface quality.

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Table 1. AWJC process parameters and their levels

Parameter	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

Table 2. Measured average values of R_a and K_t for the three varieties of composites

Sl. No.	Glass-epoxy		Carbon-epoxy		Kevlar-epoxy	
	R_a (µm)	K_t (degree)	R_a (µm)	K_t (degree)	R_a (µm)	K_t (degree)
1	8.10	3.50	8.00	2.04	8.20	3.44
2	8.10	3.60	8.00	2.04	8.20	3.44
3	8.10	2.76	8.00	2.04	8.20	3.44
4	6.50	2.74	7.60	1.83	7.80	2.65
5	6.50	2.75	7.60	1.83	7.80	2.65
6	6.50	2.50	7.60	1.83	7.80	2.65
7	4.90	2.50	7.20	1.01	7.40	2.24
8	4.90	2.50	7.20	1.01	7.40	2.24
9	4.90	3.10	7.20	1.01	7.40	2.24
10	5.90	3.10	6.40	1.55	7.30	3.15
11	5.90	3.10	6.40	1.55	7.30	3.15
12	5.90	2.40	6.40	1.55	7.30	3.15
13	4.40	2.40	6.20	0.96	5.20	2.16
14	4.40	2.40	6.20	0.96	5.20	2.16
15	4.40	3.40	6.20	0.96	5.20	2.16
16	7.50	3.40	7.50	0.87	7.50	3.10
17	7.50	3.40	7.50	0.87	7.50	3.10
18	7.50	2.10	7.50	0.87	7.50	3.10
19	3.90	2.10	5.90	0.86	3.95	1.42
20	3.90	2.10	5.90	0.86	3.90	1.42
21	3.90	3.40	5.90	0.86	4.00	1.42
22	6.70	3.40	7.30	0.91	7.00	3.32
23	6.70	3.40	7.30	0.91	7.00	3.32
24	6.70	3.40	7.30	0.91	7.00	3.32
25	5.10	2.40	6.50	0.89	6.60	2.36
26	5.10	2.40	6.50	0.89	6.60	2.36
27	5.10	2.40	6.50	0.89	6.60	2.36
Mean	5.89	2.84	6.96	1.21	6.77	2.65

Table 3. Response table S/N ratio for Surface roughness and kerf taper for glass/epoxy

Factors	Surface roughness (R_a)			Kerf taper (K_t)		
	Mean S/N ratios (dB)					
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
WJP	-16.08	-15.26	-14.16*	-9.264	-9.354	-8.226*
AFR	-15.14*	-15.22	-15.15	-8.731*	-9.007	-9.106
QL	-17.4	-15.28	-12.83*	-10.768	-8.739	- 7.336*
Optimum settings	$A_3B_1C_3$					

*Optimum levels

Table 4. Response table S/N ratio for Surface roughness and kerf taper for kevlar/epoxy

Factors	Surface roughness (R_a)			Kerf taper (K_t)		
	Mean S/N ratios (dB)					
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
WJP	-17.83	-16.36	-15.08*	-8.734	-8.828	-6.976*
AFR	-15.83*	-16.35	-17.09	-7.914*	-8.526	-8.097
QL	-17.56	-17.17	-14.55*	-10.327	-8.630	-5.580*
Optimum settings	$A_3B_1C_3$					

*Optimum levels

Table 5. Response table S/N ratio for Surface roughness and kerf taper for carbon/epoxy

Factors	Surface roughness (R_a)			Kerf taper (K_t)		
	Mean S/N ratios (dB)					
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
WJP	-17.61	-16.49	-16.31*	-3.8427	-0.7475	1.0471*
AFR	-16.53*	-16.91	-16.97	-2.8964	-1.3584	0.7118*
QL	-17.61	-16.67	-16.14*	-1.3879	-2.6812	0.5261*
Optimum settings	$A_3B_1C_3$					

*Optimum levels

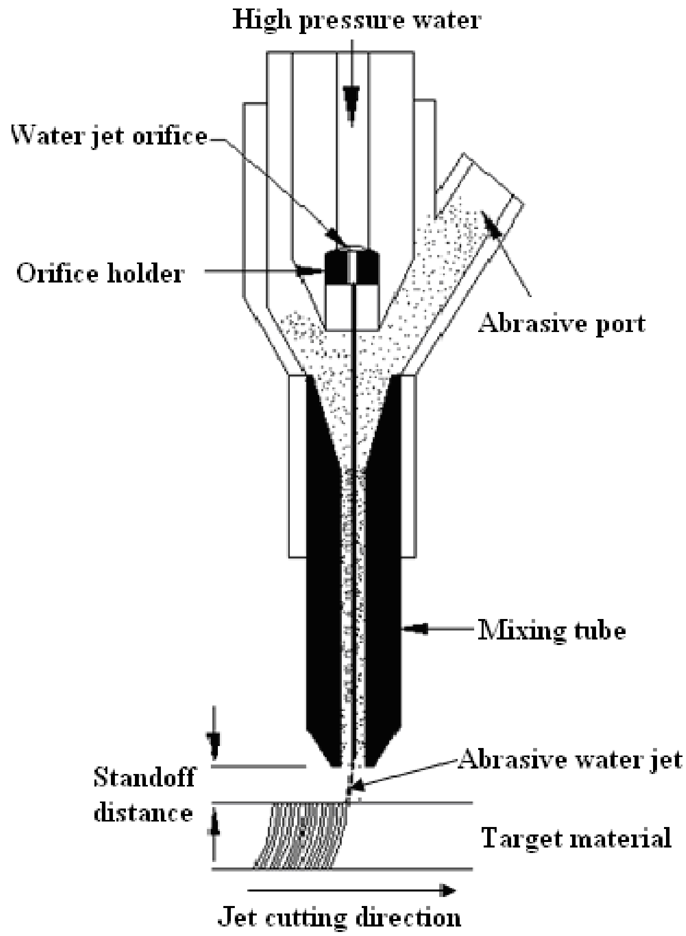


Figure 1. Schematic diagram of Abrasive water jet machining.

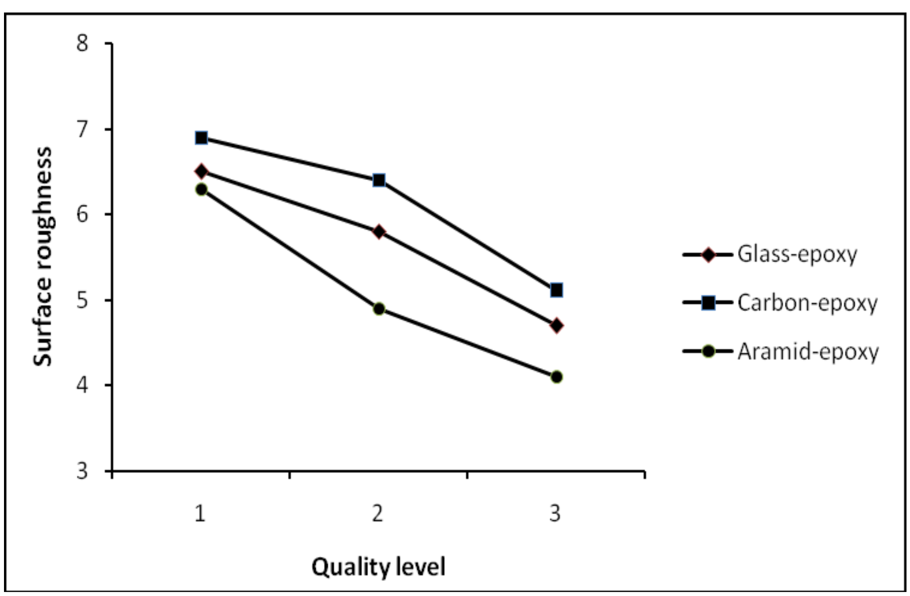


Figure 2. Effect of different quality levels (3, 4 and 5) on Surface roughness for three composite.

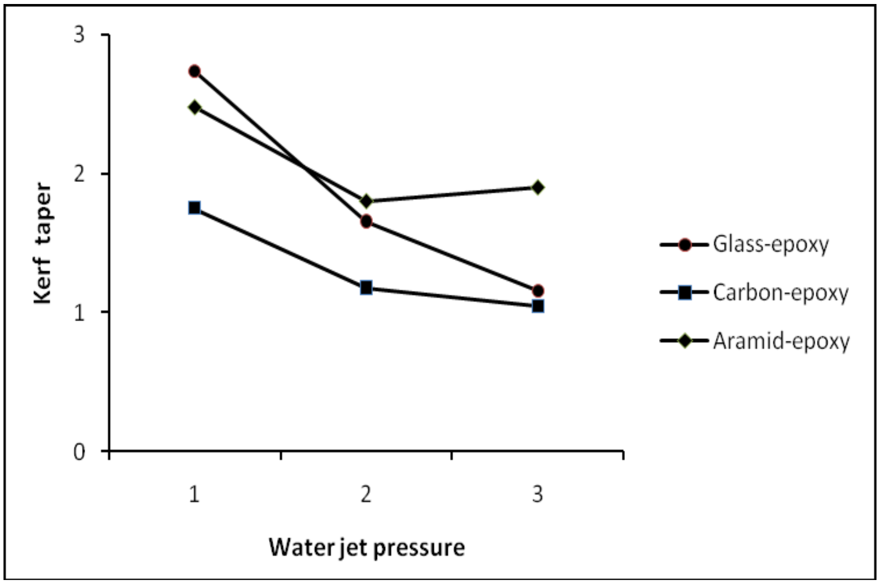


Figure 3. Effect of waterjet pressure (250, 325 and 400 MPa) on Kerf taper for three composite.

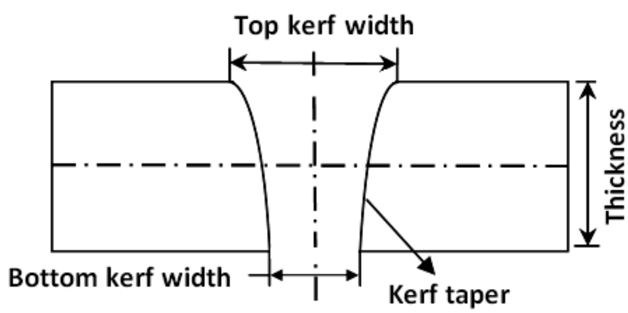


Figure 4. Schematic diagram of AWJ cut kerf geometry.

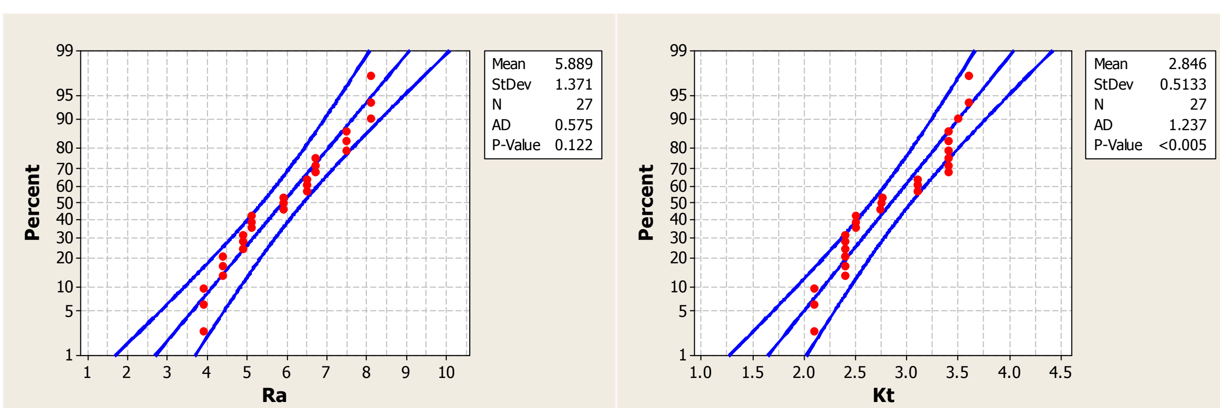


Figure 5. Normal probability plot of R_a and K_t (for glass/epoxy composite).

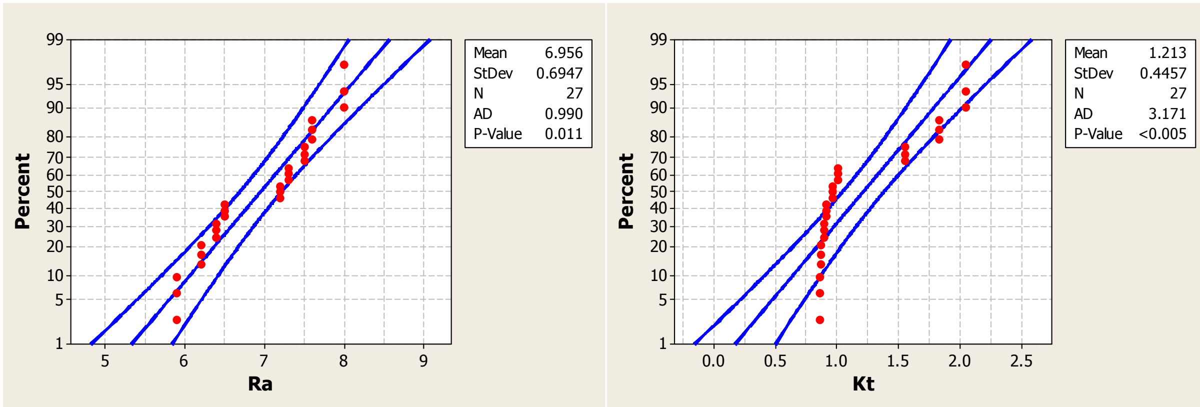


Figure 6. Normal probability plot of R_a and K_t (for carbon/epoxy composite).

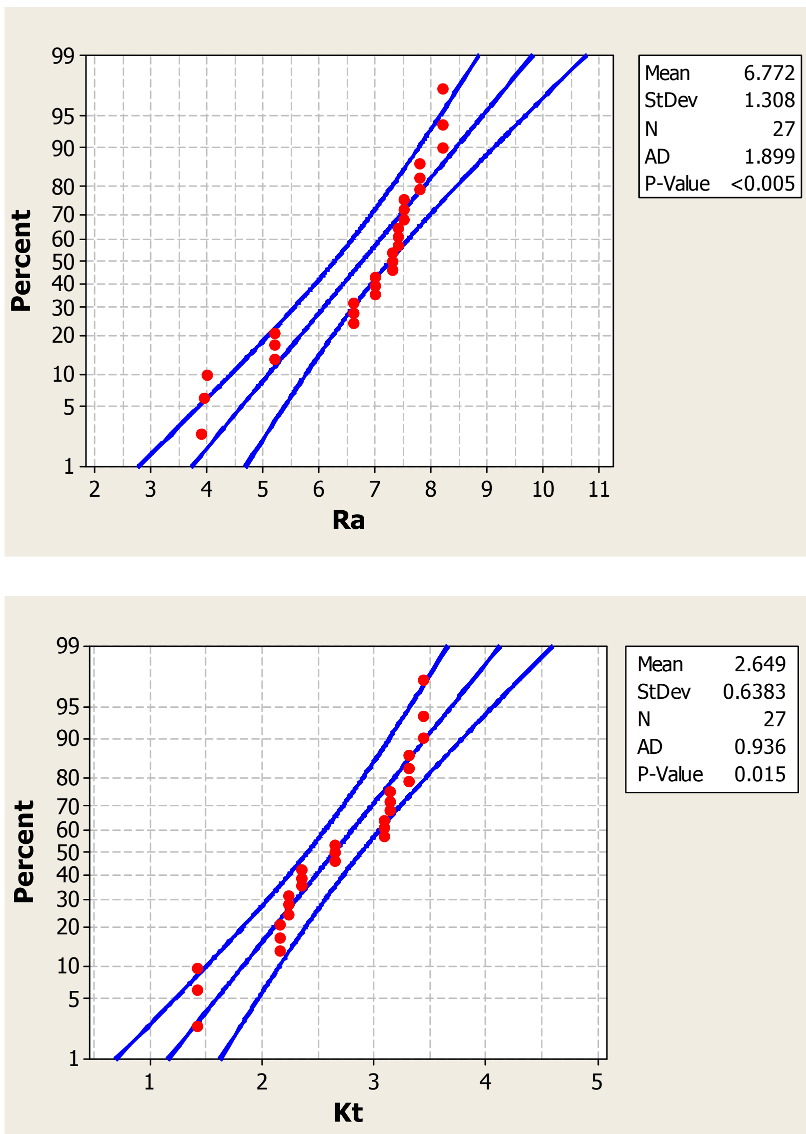


Figure 7. Normal probability plot of R_a and K_t (for Kevlar/epoxy composite).

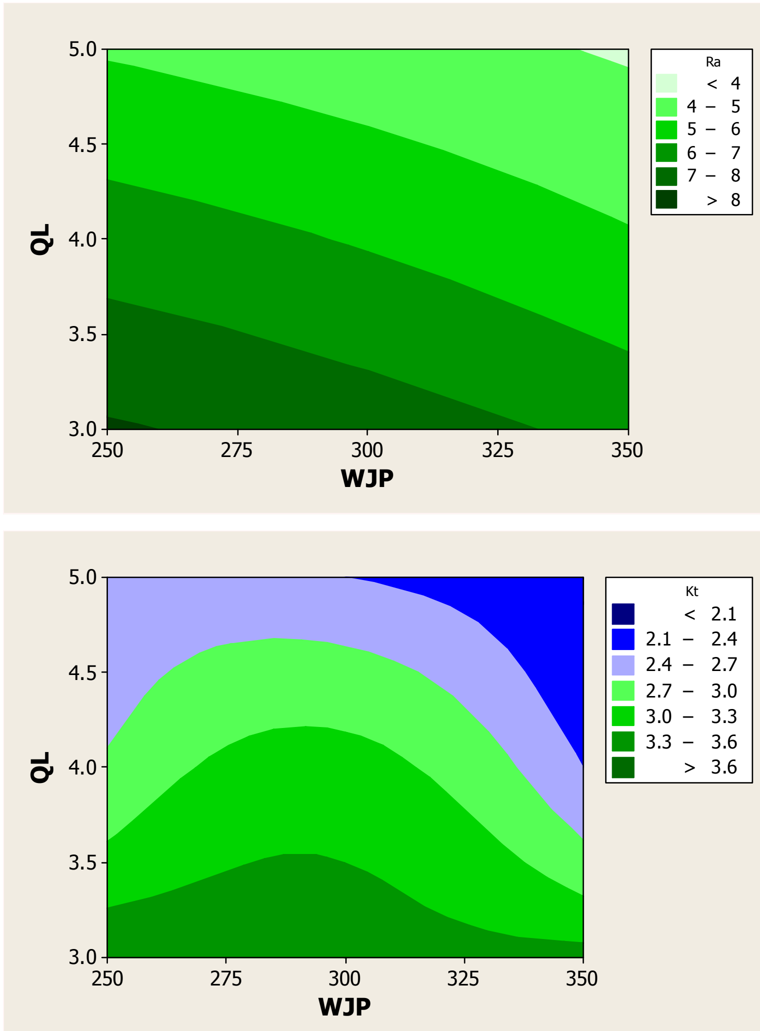
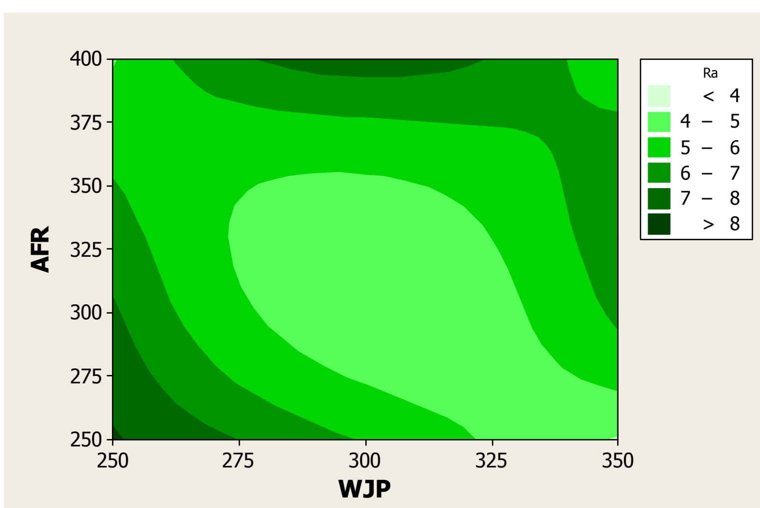


Figure 8. 3-D Contour plots showing the interaction effect of WJP and QL on R_a and K_t.



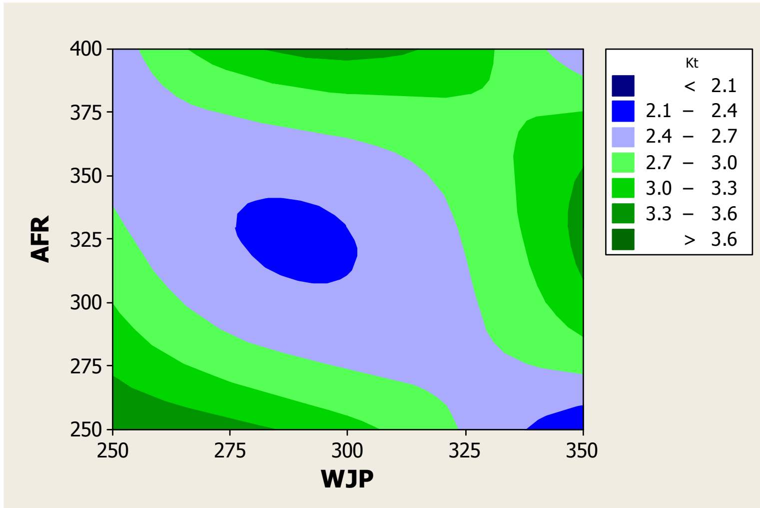


Figure 9. 3-D contour plots showing the interaction effect of WJP and AFR on R_a and K_t.

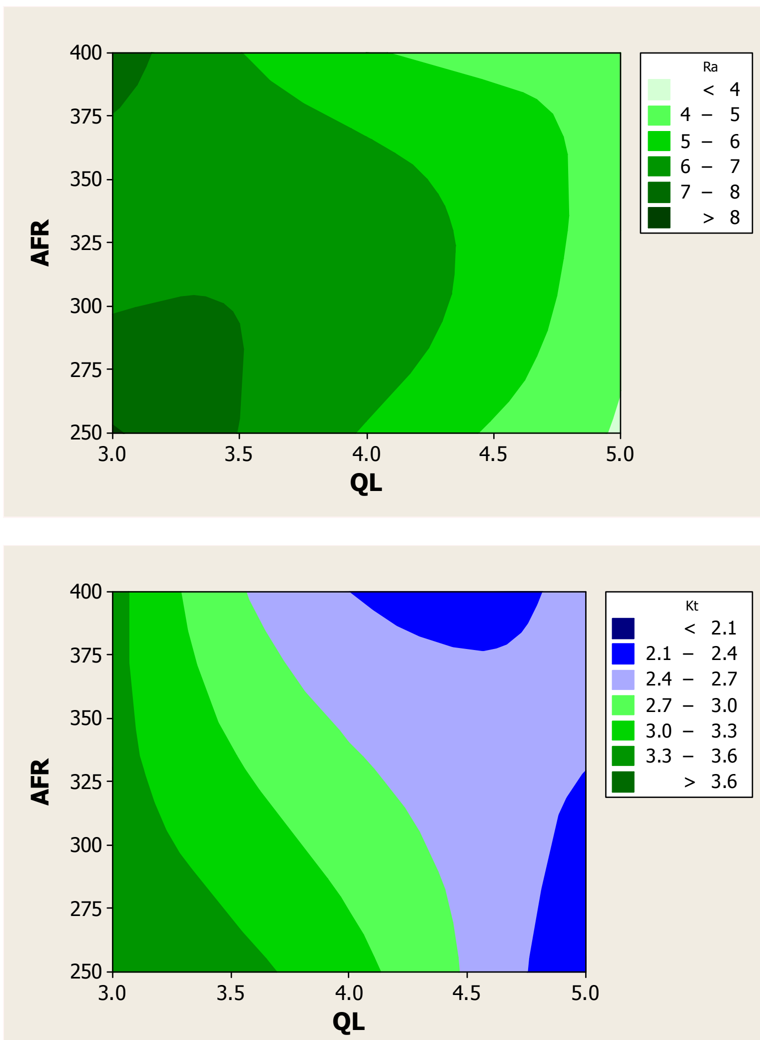


Figure 10. 3-D contour plots showing the interaction effect of QL and AFR on R_a and K_t.