# EXPERIMENTAL INVESTIGATION OF KERF CHARACTERISTICS OF KEVLAR 49 EPOXY COMPOSITE MACHINED BY ABRASIVE WATER JET

**Puneet Kumar[1], Sachin Salunkhe[2], Ravi Kant[1]**

[1]Department of Mechanical Engineering, S V National Institute of Technology, Surat, Gujarat, India
[2]Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R & D
Institute of Science and Technology, Avadi, Chennai, India

Corresponding author: Puneet Kumar, 07.me.6405@gmail.com

***Abstract:*** This paper describes the experimental study of kerf characteristics of Kevlar 49 epoxy composite machined by abrasive water jet. Influence of three process parameters, namely stand-off distance, traverse speed, and water pressure on kerf taper was investigated. Using response surface methodology, experiments were planned, conducted and then the significance of process parameters on kerf taper is studied using analysis of variance (ANOVA). It is found that the traverse rate and water pressure are significant factors followed by stand-off distance. Further, optimization of significant process parameters is performed to minimize kerf taper of the machined sample. A regression model is also developed to for prediction of kerf taper. The model predictions are found in good agreement with experimental results.

***Key words:*** Kevlar 49 epoxy composite, abrasive water jet, kerf taper, process parameters, optimization, regression model

## 1. INTRODUCTION

Advanced technology requires materials with an uncommon blend of properties that are impossible to achieve by customary ceramics, polymers, and alloys. This leads to the invention of composite materials.

Kevlar 49 epoxy composite is an aramid fiber-reinforced composite (AFRP). This leads to the invention of its major applications are not only limit to defense safety equipment like a helmet, bullet-proof jackets, etc., but also heat resistance safety equipment's, aircraft, sports' equipment and automobiles (Yahaya et al., 2016). Kevlar was first developed at DuPont laboratories in Wilmington, Unites States (University of Bristol, 2019). Later on, its commercial applications are started because of its exceptional properties like high tension moduli, toughness, and strength to weight ratio, impact resistance, longitudinal tensile strength and creep resistance (Azmir et al., 2009).

Unconventional machining of AFRP composite is challenging due to its anisotropic nature. Moreover, Unconventional machining results in poor surface finish, extreme tool wear, high-temperature rise, large cutting forces, lack of dimension accuracy, and high machining cost (Schorník et al., 2015). Among the full range of unconventional machining processes, simply abrasive water jet machining (AWJM), electro discharge machining (EDM) and laser beam machining (LBM) have received considerable attention in industries for machining of AFRP composites (Azmir et al., 2007). The benefits of these processes are high machining rates, high flexibility and ability to make a complex profile and geometries but the heat-affected zone is not observed in the machining of composites by AWJM. Poor surface finish and low machining efficiency limit the use of EDM in machining of composites (Azmir et al., 2009). Schematic diagram of AWJM is shown in Figure 1.

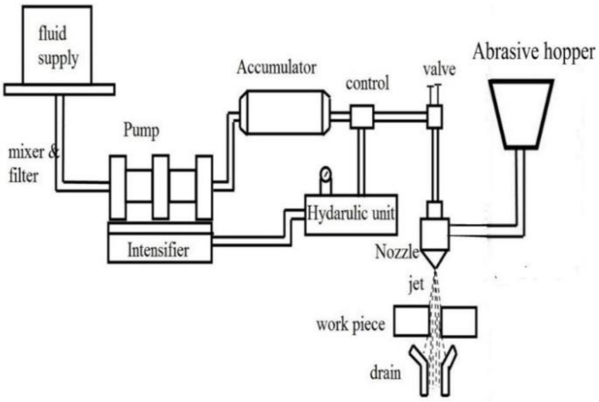

Fig. 1. Schematic diagram of AWJM [14]

Machining with an abrasive water jet is an unconventional machining process that uses the erosive effect of a high-velocity jet of water mixed with abrasive. It has been extensively used in industry for contouring or cutting two-dimension profiles from sheet stocks of most materials. Multi-axis abrasive water jet machine has been developed that can even curve complex three-dimensional contours. Abrasive water jet three-dimension contours. The abrasive water jet is capable enough to cut all most any material without any restriction imposed by its mechanical, electrical, chemical, thermal, and optical property like other unconventional machining processes.

The advantage offered by cutting with abrasive water jet machine is – Fast rate of cutting, minimal clamping, narrow kerf, and just one cutting tool. In addition, it is intrinsically ‘self-cooling’ self-cleaning and considered eco-friendly. Since it uses water and sand for cutting, therefore cutting with abrasive water jet could be considered as quite a versatile machining process compared to most conventional and unconventional processes. On the other hand, limitation of this technology is –rough kerf wall, tapered kerf with striation marks, and in some case abrasive embedment and moisture absorption take place. Thus, it may not be applicable higher geometrical accuracy and surface finish is demanded or contamination of material is a serious issue. Where the quality of kerfs may be acceptable, Abrasive water jet has been proven as superior alternative machining technology. Because of these re-makeable benefits of creating profiles. By through cutting with abrasive water jet, its application has been considered for non –through or controlled-depth cutting for milling and drilling operation. Milling with abrasive water jet for creating features like grooves and pockets have been successfully implemented on harder material like most metals, alloys, ceramics, and some composites within the quality acceptable for the application or by the user. However, scarce success has been reported on abrasive water jet cutting of softer material like wood, rubbers, and their composites. This has motivated to investigate the possibility of implementing the cutting of Kevlar fiber epoxy reinforced polymer composite with the abrasive water jet.

The schematic diagram of AWJM set up is illustrated in Figure 1. In AWM, material removal depends on the erosion caused by the impact of a jet. AWJM offer various advantages over conventional machining processes such as no heat-affected zone, high flexibility, low cutting forces, environment-friendly, high quality of surface finish, and versatility for a wide range of materials (Krajcarz, 2014). The cutting quality characteristics are defined by AWJM process is known as a kerf taper. Figure 2 demonstrates the material exclusion and kerf geometry in AWJ machined workpiece. Equation (1) is used to calculate the kerf taper angle. Kerf top width has a larger value as parallel to the bottom width. This is because of the less kinetic energy of water jet as it pierces into the material.

$$\theta = \frac{\tan^{-1}\ (w_t - w_b)}{2t} \qquad (1)$$

Where $W_t$= kerf top width, $W_b$ = kerf bottom width, and t = thickness of the specimen.

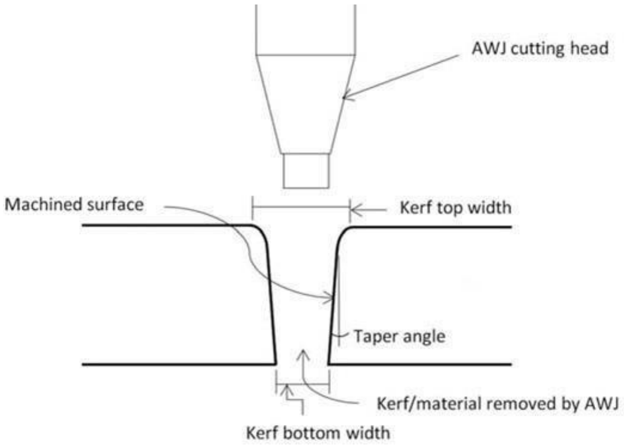

Fig. 2. Schematic representation of kerf geometry

Worldwide researchers have made efforts to investigate AWJM for machining various composites like glass-epoxy composites, fiber vinyl ester composite, graphite-epoxy composites, carbon epoxy composites, and ceramic composites to decrease kerf taper angle and surface roughness. For example, Arola and Ramulu (1996) reviewed the effect of water pressure, stand-off distance and traverse speed on kerf characteristic of AWJM of the graphite-epoxy composite. They also investigated the effect of process factor on kerf taper. Khan and Haquei (2007) studied the performance of different abrasive materials in AWJM of glass. They found that garnet is the best abrasive for machining glass. Çaydaş and Hascalık (2008) investigated the surface roughness of AWJ machined of AA7075 aluminum alloys samples and also created a regression model to forecast it. Azmir and Ahsani (2008, 2009) found out the effect of parameters on kerf angle and surface finish of AWJ machined samples of glass epoxy composite. They found that abrasive-type and water pressure are the most contributing factors. Karakurti and Aydineri (2011) studied the influence of traverse speed and water pressure on kerf taper while machining granite by AWJM process. It was found that the kerf taper graph goes down with a rise in water pressure and minimizes the traverse speed. Karakurti et al. (2014) investigated the kerf width in AWJM of granitic rocks. They found that the traverse speed and stand-off distance have a significant effect on kerf width. Kerf width increases with increase in stand-off distance and traverse speed. Dhanawade et al. (2016) have studied trends of kerf taper and surface finish with the variation in the setting of controlling factors in AWJM of carbon epoxy composite. It was found that the graph of kerf taper and surface finish goes down when we increase the water pressure and reduce in traverse speed. Abdullah et al. (2016) studied the surface quality of marble machined by AWJM. They found that the nozzle traverse speed is the most important factor followed by stand-off distance. Doreswamy et al.(2016) have study the trends that when they increase the water pressure the surface finish increased and when they increases the SOD from the work piece the surface roughness increased by 9.22%. Selvakuma et al. (2018) was observed that when the diameter of the jet was increased MRR also increased. MRR is directly proportional to the diameter of the jet. Material thickness and stand-off distance was indirectly proportional to the surface roughness. Vigneshwaran et al. (2018) concluded that (AWJM) is one of the best advanced non-conventional machining processes for machining of fiber-reinforced polymer composites. Kumar and Kant (2019) studied the influence of process parameter on kerf taper and surface roughness and find out the most significant parameter.

From the critical review of available literature, it can be concluded that many researchers have made efforts to study AWJM of carbon epoxy composite, granite hybrid composites and glass epoxy composite, etc. for improving surface finish, kerf taper, material removal rate, and depth of cut. Researchers have also optimized process parameters and developed mathematical models for response measures. But very less work has been described on AWJM of Kevlar 49 epoxy composite. In the present study, the effect of process parameters on kerf properties of AWJ machined samples of Kevar 49 epoxy composite is investigated. Three process parameters namely stand-off distance, traverse rate, and water pressure is considered. This paper is arranged as follows: section 2 describes experimental setup; section 3 presents experimental design; section 4 presents results and discussion; section 5 discusses the development of the predictive model for kerf taper, and section 6 relates to optimization of process parameters. Finally, the present study is concluded in section 7.

## 2. EXPERIMENTAL WORK

In the present study, Kevlar 49 epoxy composite is used as workpiece material for experimentation. Mechanical properties of this composite are given in Table1. The composite was manufactured by infusion process followed by furnace curing of 10hrs. The thickness of the laminates is 14.50mm. All the experiments have been conducted on AWJ machine (Flying arm model) at M/s ShreejiAn innovative International Ltd., Surat, India. The machine is depicted in Figure 3.

Fig. 3. AJM Setup (Courtesy: M/s Shree jiAinnovative International Ltd.)

Specifications of abrasive water jet machine are given in Table 2.

Table 1. Mechanical properties of Kevlar 49 epoxy composite

| Property | Unit | Value |
|---|---|---|
| Interlaminar Shear Strength | N/mm$^2$ | 22.720 |
| Compressive strength | MPa | 59.42 |
| Compressive Modulus | GPa | 5.05 |
| Tensile strength | MPa | 428.44 |
| Tensile Modulus | GPa | 18.03 |
| Elongation% | - | 5.59% |

Table 2. Specifications of abrasive water jet machine

| | |
|---|---|
| Cutting area X-axis: | 1300mm to 2000mm |
| Cutting area Y-axis: | 1300mm to 12000mm |
| Cutting area Z-axis: | 150mm to 310mm |
| Traverse speed: | Up to 10000mm/min |
| Positional accuracy | - ± 0.04mm |
| Repeat accuracy | - ±0.04mm |

Machining of Kevlar 49 epoxy composite is done by computer operated flying arm AWJ machine. The machine is fortified with the high-pressure pump which has the highest pressure limit of 400MPa. An abrasive hopper is used to store and supply the abrasive to the machine. The flow of abrasives is controlled with the help of the dial indicator. As the motive of the present work is to diminish the kerf angle. High quality of garnet abrasives particles with a mesh size of 80µm was used for the experiments. The diameter of orifice, nozzle and cutting angle were kept constant which are shown in Figure 3.

## 3. EXPERIMENTAL DESIGN

In the current study, three process parameters namely stand-off distance, traverse speed, and water jet pressure is considered. Response surface methodology (RSM) with the central composite design is used for the design of experiments which suggests 20 experiments. As given in Table 3, five levels of factors are selected for the present work on the basis of literature review, trial experiments and existing machine setup.

Table 3. Selected levels of process parameters

| Process Parameter | Unit | -1 | -2 | 0 | 1 | 2 |
|---|---|---|---|---|---|---|
| Water pressure | MPa | 160 | 170 | 180 | 190 | 200 |
| Stand-off distance (SOD) | mm | 1 | 2 | 3 | 4 | 5 |
| Travers speed | mm/min | 50 | 100 | 150 | 200 | 250 |

On the basis of the design of experiment and levels of factors, 20 samples of thickness 14.5mm of Kevlar 49 epoxy composite are machined as shown in Figure 4. After experimentation, the kerf taper angle of machined sample is measured by the vision measurement system (Rapid IV 2016jLX) as shown in Figure 5. The bottom kerf width is reserved at a uniform height of 5mm from top kerf width. The number of experiments and the value of the kerf angle are depicted in Table 4.

Table 4. Design of experiment and Measured kerf taper

| Sr. No. | WP [MPa] | SOD [mm] | TR [mm/min] | Top width [mm] | Bottom Width [mm] | Kerf Taper Angle [degree] |
|---|---|---|---|---|---|---|
| 1 | 170 | 2 | 100 | 1.47940 | 1.23046 | 0.59460 |
| 2 | 190 | 2 | 100 | 1.45690 | 1.2255 | 0.55260 |
| 3 | 170 | 4 | 100 | 1.6210 | 1.46572 | 0.890040 |
| 4 | 190 | 4 | 100 | 1.45820 | 1.31692 | 0.80990 |
| 5 | 170 | 2 | 200 | 1.15030 | 0.84829 | 1.73070 |
| 6 | 190 | 2 | 200 | 1.29170 | 0.9985 | 1.68020 |
| 7 | 170 | 4 | 200 | 1.36260 | 1.02278 | 1.94730 |
| 8 | 190 | 4 | 200 | 1.1970 | 0.86710 | 1.89040 |
| 9 | 160 | 3 | 150 | 1.21950 | 0.95119 | 1.53770 |
| 10 | 200 | 3 | 150 | 1.36310 | 1.15566 | 1.18900 |
| 11 | 180 | 1 | 150 | 1.45590 | 1.31809 | 0.79000 |
| 12 | 180 | 5 | 150 | 1.45790 | 1.20840 | 1.43000 |
| 13 | 180 | 3 | 50 | 1.7680 | 1.7230 | 0.25800 |
| 14 | 180 | 3 | 250 | 1.17380 | 0.75425 | 2.40360 |
| 15 | 180 | 3 | 150 | 1.52560 | 1.27474 | 1.43780 |
| 16 | 180 | 3 | 150 | 1.47860 | 1.24876 | 1.31730 |
| 17 | 180 | 3 | 150 | 1.38450 | 1.150 | 1.34400 |
| 18 | 180 | 3 | 150 | 1.4080 | 1.17608 | 1.32920 |
| 19 | 180 | 3 | 150 | 1.43170 | 1.18511 | 1.41330 |
| 20 | 180 | 3 | 150 | 1.38490 | 1.14070 | 1.39960 |

Fig. 4. Machining of Kevlar 49 epoxy composite by AWJM

Fig. 5. Vision Measurement System [16]

## 4. RESULTS AND DISCUSSIONS

ANOVA is used to identify the significance and effect of control factor on the kerf angle. The analysis of variance (ANOVA) for kerf taper is carried out at 95% confidence level. ANOVA for kerf taper is given in Table 5. The significant of the model can be verified by F- the value of 441.38. From ANOVA, it is observed that traverse speed and water pressure are significant parameters followed by stand-off distance. Figure 6 shows predicted vs. actual values of kerf taper.

Table 5. ANOVA for kerf taper angle

| Source | Sum of Squares | DoF | Mean Square | F value | p-value Prob>F | Influence |
|---|---|---|---|---|---|---|
| Model | 5.21 | 4 | 1.30 | 441.38 | < 0.0001 | significant |
| Water Pressure | 0.32 | 1 | 0.32 | 108.09 | <0.0001 | significant |
| Stand-off distance | 0.054 | 1 | 0.054 | 18.19 | 0.0007 | significant |
| Traverse speed | 4.72 | 1 | 4.72 | 1599.76 | <0.0001 | significant |
| B2 | 0.12 | 1 | 0.12 | 39.49 | <0.0001 | |

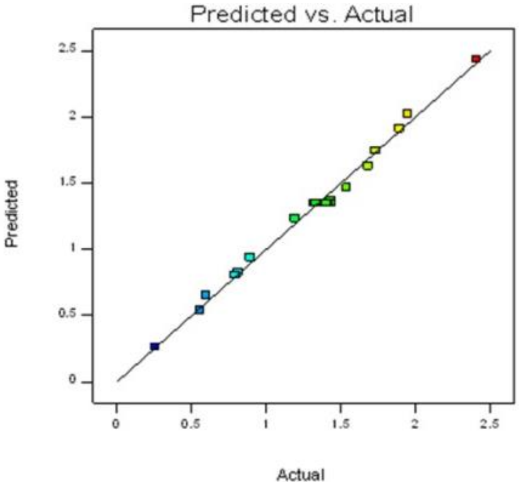

Fig. 6. Predicted vs. actual values of kerf taper

From experimentation and ANOVA, it is noticed that traverse speed and water pressure are the most significant parameters followed by stand-off distance. Figure 7 shows the influence of the traverse speed (TS) and the water pressure (WP) on the kerf taper. It is found that the kerf angle increases with increase in traverse speed. This is due to, by increasing traverse speed less number of abrasive particles comes into contact with the workpiece. Due to this, the jet fails to penetrate into the bottom of work piece and variation between top kerf width and bottom kerf width increases, which increases kerf taper angle. The maximum kerf taper is observed at 150MPa, and it decreases with increase in pressure. Kerf taper decreases with an increase in water pressure. The increase in water pressure causes an increase in particle velocity at nozzle exit and particle fragmentation inside the nozzle. This fragmentation decreases the size of the impacting particle. Also, a rise in water pressure increases abrasive water jet kinetic energy.

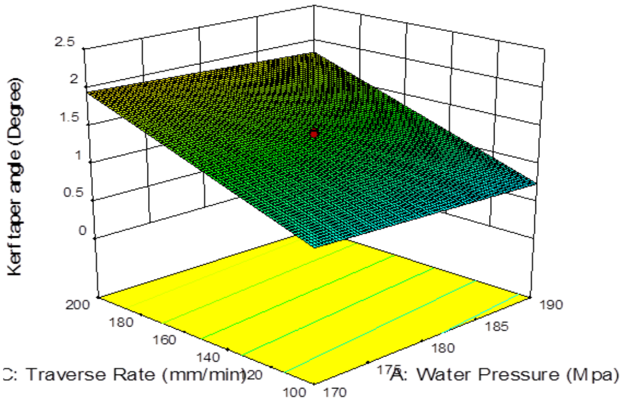

Fig. 7. Influence of WP and TS on kerf taper angle

Figure 8 shows the influence of water pressure (WP) and stand-off distance (SOD) on kerf taper. The kerf taper decreases with rising in stand-off distance (SOD). This is because of the fact that the water jet diverges with the increase in SOD and this divergence results in a higher taper angle. This diversion of the jet at low and high stand-off distance as depicted in Figures 9 and 10.

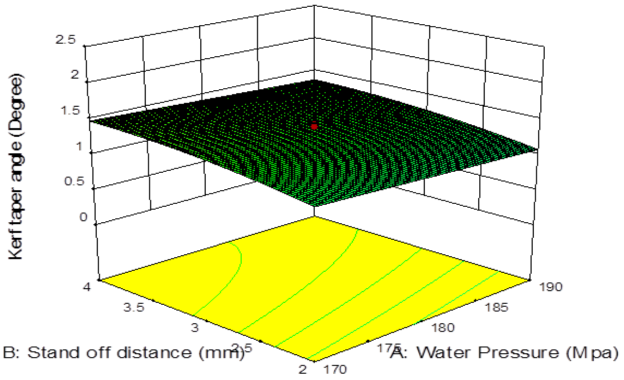

Fig. 8. Influence of WP and SOD on the kerf taper angle

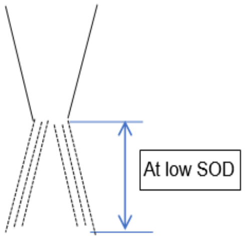

Fig. 9. Less effective area of machining sample

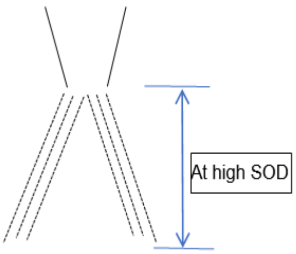

Fig. 10. More effective area of machining sample

## 5. PREDICTIVE MODEL FOR KERF TAPER

To predict the kerf taper from the experimental results, a regression model is developed. The regression model is established based on the significant terms. The final regression equation for kerf taper in terms of coded factors is given in equation (2).

$$\text{Kerf taper} = 1.35 - 0.58 \times A + 0.14 \times B + 0.54 \times C - 0.065 \times B^2 \quad (2)$$

The predicted and adjusted R2 value of 0.9808 and 0.9893 shows reasonable agreement

## 6. OPTIMIZATION OF PROCESS PARAMETERS

Optimization of significant factors is performed to diminish kerf taper of machined samples. The criteria for optimization are shown in Table 6. Figure 11 shows the bar graph for the desirability of kerf taper angle and all other factors. The value of desirability for all factors is 1, and values near one are very close to the normalized value. The desirability value for kerf taper is 0.8677 and the mutual desirability value of all process parameters and kerf taper angle is 0.8677. Both values are close to 1 and hence it is acceptable.

Table 6. Criteria for optimization

| Sr. No. | Parameter responses | Goal | Lower Limit | Upper Limit | Optimized value |
|---|---|---|---|---|---|
| 1 | Stand-off distance [mm] | In range | 2 | 4 | 2 |
| 2 | Water pressure [MPa] | In range | 170 | 190 | 190 |
| 3 | Traverse speed [mm/min] | In range | 100 | 200 | 100 |
| 4 | Kerf taper [degree] | Minimize | 0.25796 | 2.40363 | 0.541638 |

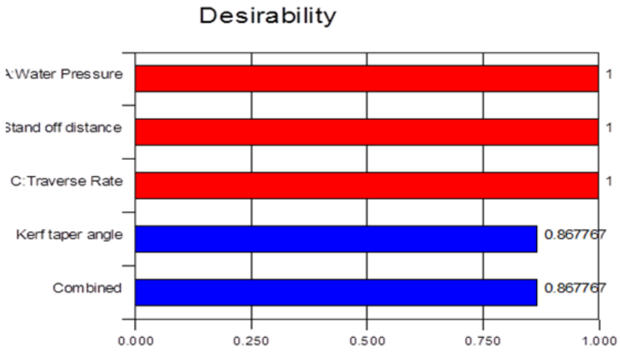

Fig. 11. Bar graph of desirability of process parameter and kerf taper

## 7. CONCLUSIONS

In the present work, an experimental study of kerf taper of Kevlar 49 epoxy composite machined by

AWJM is described. It is found that traverse speed and the water pressure are the most significant factors trailed by the stand-off distance influencing kerf taper in machined samples. Kerf taper decreases with decrease in traverse speed and stand-off distance. Also with the rise in water pressure, kerf taper reduces. Further, the predictive model for kerf taper has also been developed and optimization of significant factors has been performed to minimize kerf taper angle.

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