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EXPERIMENTAL INVESTIGATION AND OPTIMIZATION OF KERF CHARACTERISTICS IN ABRASIVE WATERJET TREPANNING OF THICK KEVLAR-EPOXY COMPOSITES

Tauseef Uddin SIDDIQUI[1], Mukul SHUKLA[2]

Abstract: *Abrasive water jets (AWJs) are widely useful for machining, shaping and drilling aerospace grade materials like composites, ceramics and super alloys unlike other advanced machining processes due to its non-thermal characteristics. However, due to the inherent characteristics of AWJs, some striation marks are observed at the exit side of jet which results in an inferior surface quality and necessitates finishing operations. Therefore, to obtain economic and better quality AWJ products, optimum selection of process parameters is very important and critical. This paper embodies an experimental investigation for optimized design in AWJ trepanning of aircraft grade Kevlar-epoxy composites using design of experiment based Taguchi method. In the present paper, kerf characteristics such as surface roughness have been selected for evaluating the AWJ drilling performance. Four major operating parameters namely, water jet pressure, abrasive flow rate, quality level and abrasive grit size have been considered for experimentation. A mixed Taguchi orthogonal array* $L_{18}(2^1 \times 3^7)$ *is used for carrying out exhaustive experimental work. It was found that higher water jet pressure and quality level, 120 mesh (125 µm) fine garnet abrasive and medium value of abrasive flow rate is desirable for better surface finish. 3-D micrographs obtained by using image analysis software clearly showed the improvement in surface finish at the optimum settings in comparison to the initial ones. Delamination crack length was also determined by SEM.*

Key words: *Abrasive water jets (AWJs), process parameters, optimum selection, Kevlar-epoxy composites, roughness, image analysis, delamination crack length.*

1. INTRODUCTION

The drilling process involves creating holes of right circular cylindrical shape, traditionally by employing rigid twist drills. In deep-hole applications, removal of the chips and cooling of the cutting front are significant issues involved with traditional drilling operations, especially for difficult-to-cut materials such as composites, ceramics and super alloys etc. However, the AWJ drilling or piercing process involves impacting the target material with an abrasive-laden waterjet, normally directed to a target surface, to penetrate the material by erosion. Since both the eroded material and any generated heat can leave the cavity with the out-flowing slurry, the issues of chip removal and cutting front cooling are avoided as found by Hocheng and Tsao [1].

Drilling is increasingly used operation for machining composites since components made out of composite materials are usually near net shaped, thus requiring holes for assembly integration. Drilling difficult to machine materials such as ceramics, glass, high nickel alloys used as gas turbine materials, etc., pose a formidable challenge to trepanning with conventional drill bits. Deep hole drilling using laser causes undesirable surface characteristics such as burr formation due to considerable heating of the workpiece and need of additional finishing operations. AWJ drilling is a viable alternative for this purpose. Hashish demonstrated [2] that different techniques such as rectangular shaped AWJ with rotating workpiece, stationary workpiece with oscillating jet, or stationary workpiece with rotating jet can be adopted to produce high quality deep holes. Depth monitoring in opaque materials during AWJ drilling of small diameter blind holes is very difficult to perform without interruptions. In order to control blind hole drilling process efficiently, depth monitoring is the primary issue, which is being addressed by the investigators. Raju and Ramulu [3] developed a semi-empirical transient numerical model for prediction of the depth of AWJ drilling based on the principle of conservation of momentum. This drilling model was providing close correlation at medium drilling depth. Kovacevik et al. [4] adopted a different approach to address this issue. Their investigations demonstrated that acoustic emission signal generated during the AWJ drilling process can be used as an effective tool for monitoring the drill depth. This investigation also showed that acoustic emission sensing technique provides critical information and more insight into the material removal mechanism during the AWJ drilling process. Yong and Kovacevic [5] developed a theoretical model to construct an arbitary particle laden jet flow by fractal point sets which was demonstrated for predicting AWJ

[1] Lecturer, Mechanical Engineering Department, I.E.T, M.J.P. Rohilkhand University, Bareilly-243006, India, TEL: +91-9410405980, Fax: +91-581-2524232,
E-mail: tauseefus@gmail.com
[2] Senior lecturer, Mechanical Engineering Science Department, University of Johnesberg, South Africa,
E-mail: mshukla@uj.ac.za

drilling depth. Two dimensional dynamic photoelasticity method was developed by Ramulu et al. [6] to record the photoelastic stress pattern associate with AWJ drilling and cutting. These fringe patterns were used to identify the transient stress fields adjacent to the drilled hole during the initial crater generation and crack propagation. Ho-Cheng [7] discussed an analytical approach to study the delamination during drilling by water jet piercing. Their model predicted an optimal water jet pressure for no delamination as a function of hole depth and material parameter. Ramulu et al. [8] reviewed and investigated the AWJ drilling for various materials (steel, aluminium, glass, titanium and polycarbonate). It was found that water pressure, abrasive flow rate and drilling time significantly affected the dimensions and accuracy of the AWJ drilled holes. Hocheng and Sao [1] studied various non-traditional drilling techniques and observed that WJ drilling can be effectively used to make fine holes of medium to large diameter, by contour cutting very speedily. They found that delamination can be eliminated by reducing the jet speed while the piercing capability deteriorates. Akkurt [9] studied the AWJ drilling of 99% pure aluminum, Al-6061 aluminum alloy, AISI 304, AISI 1030 and cold working tool steel. The effects of thickness and material type on the drilling time were investigated and discussed. It was found that there is not much difference between the drilled surface and the base material hardness. Micro photographs study showed that drilling does not affect the micro structure and mechanical properties of the material. It was found from the literature review that no work has been reported till now on AWJ trepanning of thick Kevlar-epoxy composites used in ballistic applications. Therefore in the present work, optimization of kerf characteristics such as surface roughness has been attempted in order to produce better quality holes using AWJ trepanning.

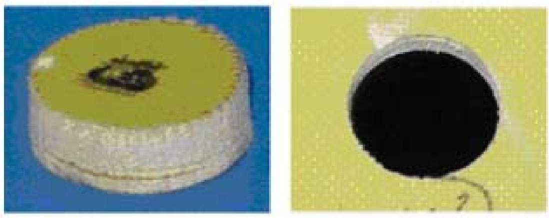
2. EXPERIMENTAL PROCEDURE

In the present experimental work, the CNC controlled OMAX 2652® Machining Centre is used for AWJ drilling of thick kevlar-epoxy composite samples. It uses a crankshaft driven high pressure pump having capacity (20 hp/400MPa), a precision X-Y table of work envelope 52″×26″ and accuracy of motion between 0.051 mm to 0.076 mm, a control system software to control the movement of AWJ nozzle head, an abrasive feed system to deliver a predetermined continuous flow of abrasive using an air controlled valve, an AWJ nozzle, and a water reservoir catcher system to absorb the energy of the jet. The orifice diameter (0.33 mm), mixing tube diameter (0.762 mm) and garnet abrasive size (80#) were kept constant. This size of garnet abrasive is widely used in various industrial applications of AWJ machining. In this work, 6 mm thick Kevlar-epoxy composite samples were fabricated by the hand layup technique using fine Kevlar fiber woven mat of thickness 0.4 mm, epoxy resin (LY 556) and hardener (HY 951). The pressure and temperature were maintained at 150 kgf/cm^2 and 130°C respectively for 20-25 minutes in a hot-press. Intermittent degassing was carried out to remove the entrapped gases. The sample was finally cooled down to room temperature and the cured sample heated in an oven up to 80°C to remove the trapped moisture. This material is especially used in anti-ballistic military applications like tank shells, armour etc. In the present research work, kerf characteristics such as surface roughness have been selected for evaluating the AWJ drilling performance. Four major operating parameters namely, water jet pressure, abrasive flow rate, quality level and abrasive grit size have been considered for experimentation. A mixed Taguchi orthogonal array L_{18} ($2^1 \times 3^7$) is used for carrying out experimental work. The surface roughness of trepanned holes was measured using a Mitutoyo Surftest SJ-201 (diamond stylus of 5 μm tip radius and 0.01 μm resolution) as shown in Fig. 1. The R_a was measured at the top and bottom surface of the specimen to avoid jet striation effect at entry and exit side. Two replicates of the samples were used for taking the measurements and their average values have been used (Table 1).

Table 1

Measured values of R_a as per L_{18} *OA*

S No.	Mesh size (A)	*WJP* (B)	*AFR* (C)	*QL* (D)	R_a (μm)
1	120	200	0.15	1	8.65
2	120	200	0.225	3	3.84
3	120	200	0.3	5	3.21
4	120	275	0.15	1	6.29
5	120	275	0.225	3	3.06
6	120	275	0.3	5	2.56
7	120	350	0.15	3	2.61
8	120	350	0.225	5	2.85
9	120	350	0.3	1	4.44
10	80	200	0.15	5	3.18
11	80	200	0.225	1	5.96
12	80	200	0.3	3	3.73
13	80	275	0.15	3	1.65
14	80	275	0.225	5	1.24
15	80	275	0.3	1	4.34
16	80	350	0.15	5	0.76
17	80	350	0.225	1	6.45
18	80	350	0.3	3	2.65



a b

Fig. 1. Different features of AWJ drilled thick Kevlar-epoxy samples: *a* – delamination and; *b* – fibre damage.

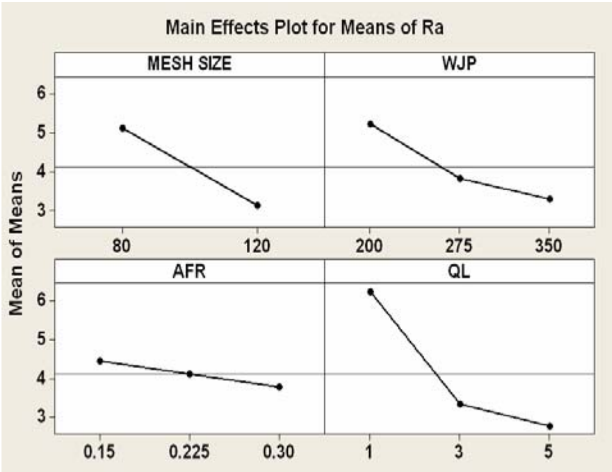
3. RESULTS AND DISCUSSION

It was found that higher value of WJP and QL, finer abrasive and lower value of AFR are desirable for better

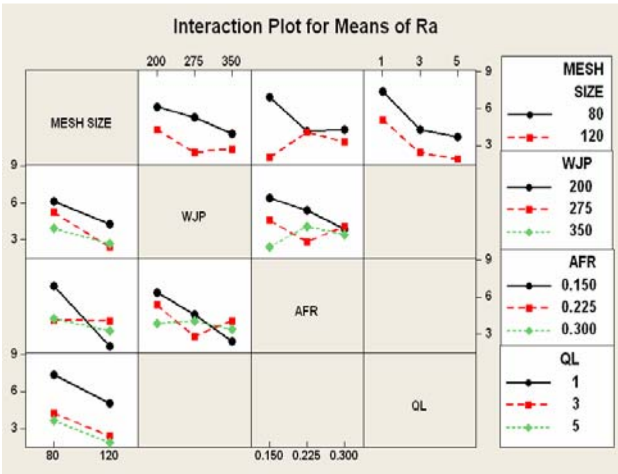
Table 2

Optimum parameter settings for minimum R_a

Levels	Mesh size (A)	*WJP* (B)	*AFR* (C)	*QL* (*D*)
1	–9.173*	–13.715	–10.973	–15.791
2	–13.484	–10.340	–10.748*	–10.746
3	–	–9.930*	–12.265	–7.448*
Delta	4.311	3.785	1.517	8.343
Rank	2	3	4	1
Optimum combination	$A_1B_3C_2D_3$			



a

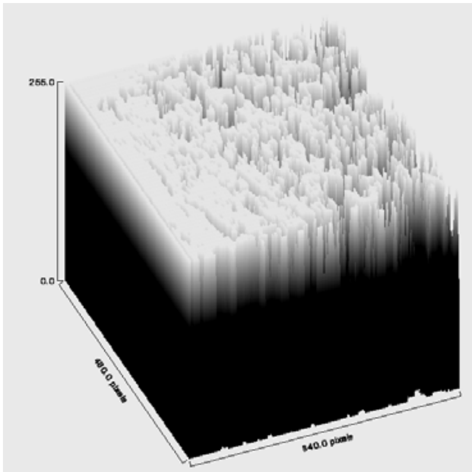


b

Fig. 2. *a* – Main and *b* – interaction effect plots for mean R_a.

surface finish (Table 2 and Fig. 2a). From a physical point of view of the AWJM process, higher water jet pressure increases the ability of material removal, leading to decrease in surface roughness. Finer abrasive size and 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 as found by Momber and Kovacevic [10]. Higher quality level (lower traverse speed) allows more overlapping cutting action and more number of abrasive particles to impinge the surface, thereby improving the surface finish. Mesh size (40.60%), quality level (18.19%) and water jet pressure (22.71%) are having more significant effect on the AWJ cut hole surface roughness in comparison to their first order interaction effects (with contribution of 4.32% and 1.03%) as shown in Fig. 2b. Figure 3a shows roughness profile obtained along the length of AWJ cut specimen at (quality level -1) using the Image J 1.34s software. It can be observed that striated surface profile is obtained mainly at the exit of the AWJ due to higher traverse speed (shown in terms of grey values as the height of different peaks and depth of different valleys). It can also be observed from Fig. 3b that a fairly constant cut surface profile (small difference in maximum and minimum grey values) is obtained along the length of cut (distance in pixels) due to negligible effect of the deflection of jet at lower traverse speed (higher water jet pressure and quality level, 120 mesh (125 µm) fine garnet abrasives and lower value of abrasive flow rate. Some amount of delamination was observed in few Kevlar-epoxy composite samples (Fig. 1) at the exit side of the hole as shown by SEM images (Figs. 4a, 4b and 5). The extent of delamination is dependent on the AWJ cutting parameters settings and ultimately affects the overall surface integrity of cut specimen. By positioning the starting and end point of delamination zone using SEM image, crack length has been determined as follows:

- Initial crack position (x_1) = 4.058.
- Final crack position (x2) = 0.6911.
- Delamination length $\Delta x = |x_2 - x_1| = 4.3047$.



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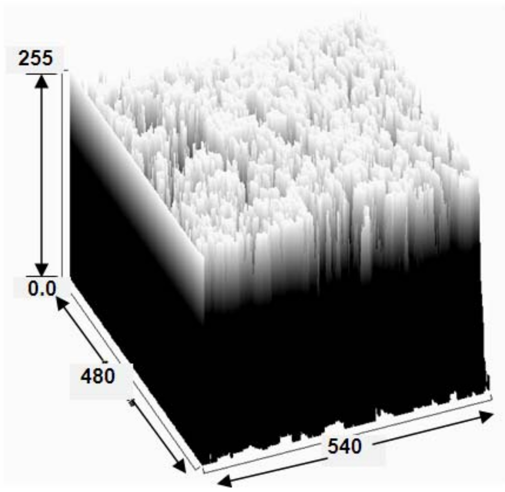
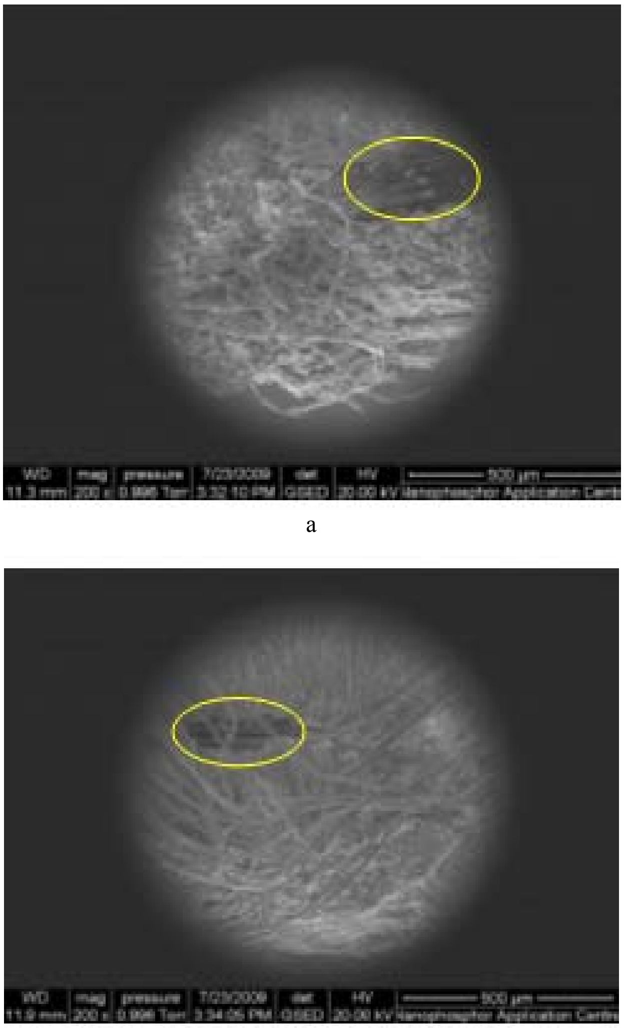


b

Fig. 3. 3-D micrographs of *a* – Striated surface and b – Smooth surface.



a

b

Fig. 4. *a* – Start and *b* – End of delamination at the bottom side of AWJ trepanned hole [11].

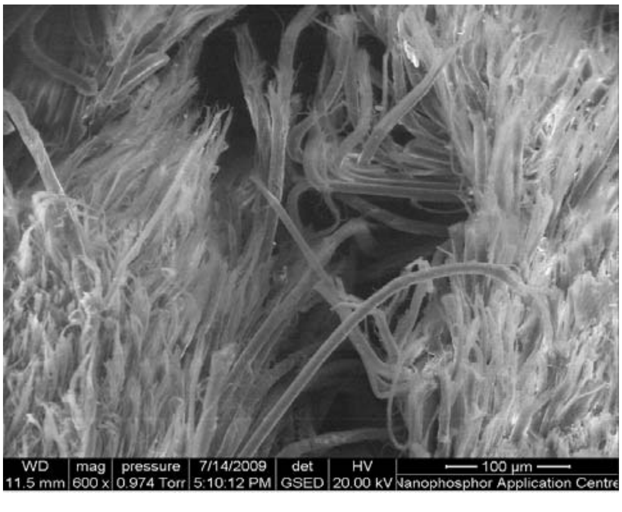


Fig. 5. SEM image of a delaminated thick kevlar-epoxy composite sample at setting 1 of L18 array.

4. CONCLUSIONS

Lower traverse speed or higher quality level is desirable in AWJ hole trepanning to obtain better dimensional accuracy required for assembly operations.

Finer abrasives produced better surface finish of trepanned holes in comparison to coarser abrasive size.

Mesh size (40.60%), quality level (18.19%) and water jet pressure (22.71%) have a more significant effect on the AWJ cut hole surface roughness in comparison to their interaction effects (with contribution of 4.32% and 1.03%).

Investigation and quantification of delamination at the bottom side of the hole has been attempted. Further studies are planned in the future for predictive modeling and minimization of delamination.

This work is likely to prove beneficial for generating superior quality holes by AWJ trepanning in thick Kevlar-epoxy composites used in ballistic applications.

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