An Investigation on Kerf Geometry for Abrasive Waterjet Cutting of Metal-Polymer-Metal Laminate

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Abstract— **Composites are finding distinct applications in various sectors such as automobile, aeroplane, marine applications. In order to make successive use of composites in various applications, machining features have to be created by machining process such as abrasive waterjet machining (AWJM) which is less sensitive to properties of composites. The present work deals with investigation of kerf geometry of metal-polymer-metal laminate machined by abrasive waterjet.ANOVA is applied to determine significant control factor affecting kerf geometry.Finally,predictive models for kerf geometry are developed using regression analysis**.

Keywords— **AWJM, metal-polymer-metal laminate, kerf geometry, ANOVA, regression analysis.**

I. INTRODUCTION

Abrasive waterjet machining as an unconventional machining process that had been used successfully in various industrial operations such as milling, cutting, surface preparation, peening, etc .This process offers various distinct advantages such as no thermal distortion, low cutting forces, high machining versatility [1].Considerable efforts have been made by various researchers from last 3 decades to study this cutting technology from various points of view such as depth of penetration, material removal, surface roughness, kerf geometry in order to have thorough understanding of the process.

The use of composite materials becomes prominent in today's advanced manufacturing technology. Because composite materials possess unusual combination of properties which cannot be obtained from single material. The most common advantages of composite materials are high strength to weight ratio, good corrosive resistance, easy availability and cost effectiveness.

The metal-polymer-metal laminates have been used successively in body panels of Audi A-2.It offers various advantages such as reduction in the metallic sound and obviates the need of damping material. It was also been used in non-transport applications such as airfreight container catering trolleys, laptop containers,X-ray film cassette containers due to its low weight and good resistance to dent and damage[2]. The use of laminate in various applications as discussed earlier shows that laminate is of highly interest and needs to be focused from machining point of view because in order to use the laminate in various applications, machining features such as holes, key ways, slots have to be produced without affecting properties of laminate. Abrasive waterjet machining is most suitable method for machining laminates because of its distinct advantages [1].

M. Ramulu *et al.* have conducted research on influence of abrasive waterjet cutting conditions on the surface quality of graphite/epoxy laminates [3] and M.A. Azmir *et al.*have presented study of abrasive water jet machining process on glass/epoxy composite laminate [4]. M.A. Azmir *et al.* studied the effect of abrasive water jet machining parameters on aramid fibre reinforced plastics composite [5].J.Wang has presented abrasive waterjet machining of polymer matrix composites-cutting performance, erosive process and predictive models [6] while C. Ma *et al.*have developed correlation for predicting the kerf profile from abrasive water jet cutting [7]. D.K. Shanmugam *et al.* have presented an investigation on kerf characteristics in abrasive waterjet cutting of layered composites [8].

Therefore, it seems that study of kerf characteristics of metal-polymer-metal laminate is rarely found therefore the present work deals with study of kerf characteristics of aluminium-polyester-aluminium cut by abrasive waterjet

II. EXPERIMENTAL SET-UP & PROCEDURE

2.1. *Material*

Aluminium-Polyester-Aluminium laminate composed of 5 layers of Aluminium and 4 layers of Polyester was used for cutting in this present work. The laminates were prepared by procuring necessary materials namely aluminium and polyester. The aluminium sheet of thickness 1 mm and polyester resin was procured from local market. The full factorial design was used, which leads to reduce the number of experiments to 27 i.e. number of runs to be executed is 27.

The wooden base was made for holding the aluminium sheets. These sheets were having a gap of 1 mm between them. The general purpose polyester was poured in the gap between aluminium sheets.

The initiator and accelerator were added in the proportion of 1.5 % into resin to cure at room temperature. Due care was taken so that complete filling of the gaps was ensured. In order to achieve fully cured state, specimen was kept for 24 hours for curing at room temperature. Later, specimen was kept for 4-5 days for post curing before cutting was performed.

2.2. *Experimental Set-up*

All experiments in present study were performed on Abrasive Waterjet Machine with DARDI series UHP pump DIPS6-2230.The machine details are tabulated as follows:

TABLE I
MACHINE DETAILS

Max. Waterjet pressure (MPa)	Max.Traverse Rate of nozzle (mm/min)	Nozzle Diameter (mm)	Orifice Diameter (mm)	Abrasive Type and Size	Power (KW)	Max.nozzle movement along X,Y,Z axes (mm)
24-300	6000	0.7	0.25	Garnet, # 80	3.7	1300,1300,150

2.3. *Experimental Design*

The cutting tests were performed using 3^3 full factorial design.3^3 indicates three factors at three levels. The details of control factors and levels are tabulated as follows:

TABLE II
DETAILS OF CONTROL FACTORS

Factors with unit ↓	**Levels →**	**Minimum**	**Average**	**Maximum**
Waterjet Pressure (A) MPa		72	96	120
Traverse Rate (B) mm/min		150	225	300
Standoff Distance (C) mm		2	3	4

2.4. *Experimental Procedure*

The laminates were cut by executing 3^3 full factorial design. The response variables for kerf geometry were top width, bottom width and ratio of top width to the bottom width called as kerf taper ratio. The proper working of all components of abrasive waterjet machine such as compressor, ultra high pressure pump, and abrasive feeding system was ensured. The level of water in the cutting water tank was also checked. Then compressor was started to have sufficient air pressure required for accelerating the abrasive waterjet. Then control panel of CNC abrasive waterjet machine was turn ON. The CNC program was entered and executed. Once the cutting was over, the water in the pipeline was drained and control panel was turned OFF which was followed by removing the air from compressor. Further step was to measure the effects of variation of control factors on kerf geometry.

III.PREDICTIVE MODELS

The functional relationship of dependent variables and independent variables is represented by predictive model. The dependent variables in present study were top width, bottom width and kerf taper ratio while the independent variables were abrasive waterjet pressure, traverse speed and stand-off distance respectively. The least square method of regression was applied to estimate coefficients in multiple linear regression model.

$$W_t = 0.0499\,P - 0.0041\,T - 0.2SOD - 0.8235$$

With R^2 to be 0.9013

$$W_b = 0.0421\,P - 0.0045\,T - 0.243\,SOD - 0.4419$$

With R^2 to be 0.9205

$$T_R = -0.0038\,P + 0.0009\,T + 0.0659\,SOD + 1.3199$$

With R^2 to be 0.8689

Where

W_t	Top Width, mm
W_b	Bottom Width, mm
T_R	Kerf taper ratio, mm/mm
P	Abrasive waterjet pressure, MPa
T	Traverse rate, mm/min
SOD	Stand-off distance, mm

IV. RESULTS

4.1. *Kerf Geometry*

The experiments were conducted to analyse the influence of control factors namely abrasive waterjet pressure, traverse speed and stand- off distance on the kerf geometry (Top width, bottom width and ratio of top width to bottom width).

In this experiment, the net effects of varying abrasive waterjet pressure, traverse rate of nozzle and stand-off distance on kerf geometry of metal-polymer-metal laminate were studied. In order to limit the number of experiments, design of experiment was applied. The laminates were prepared by procuring necessary materials namely aluminium and polyester. Based on practical limitations and machine range, the control factors such as abrasive waterjet pressure, traverse speed and stand-off distance were selected. The kerf geometry obtained by varying these control factors is reported in this work. The 3^3 full factorial design was applied to reduce number of experiments.

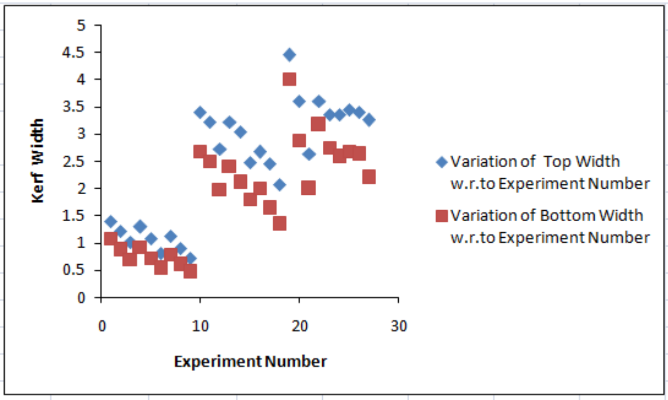

Figure 1: Variation of Kerf Width with respect to Experiment Number

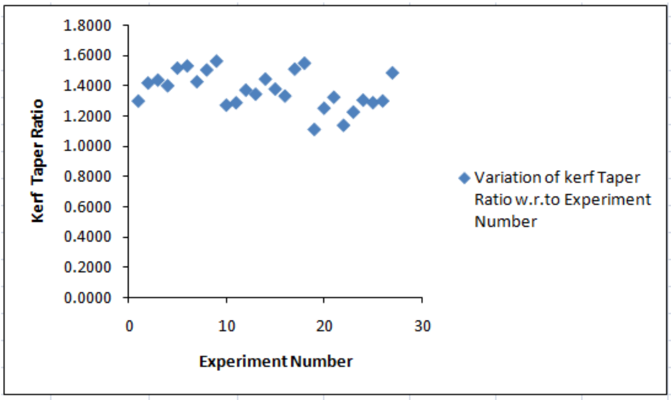

Figure 2: Variation of Kerf Taper Ratio with respect to Experiment Number

The influence of control factors on the kerf width is represented in the graph. The effects of control factors with justifications are as under:

As abrasive waterjet pressure increases, the top as well as bottom width in short kerf width increases. As abrasive water jet pressure goes on increasing, the kerf width also increases.

As increase in the abrasive waterjet increases the kinetic energy of the jet, kerf width at the top as well as bottom increases since penetration ability of the jet increases. This is clearly observed in the graph that kerf width obtained for abrasive waterjet pressure of 120 MPa is highest over that obtained for 96 MPa and 72 MPa. However, the kerf width at the bottom is less than that at the top because when the jet penetrates, its kinetic energy decreases.

As traverse speed of nozzle increases, kerf width decreases because exposure time for the jet over the workpiece decreses.As stand-off distance increases, the kerf width decreases since jet tend to diverge as distance between nozzle and workpiece increases.

Hence, in order to have uniform kerf width, traverse speed and stand-off distance should be minimum but abrasive waterjet pressure should be maximum.

Another response variable is kerf taper ratio which is nothing but the ratio of the top width to the bottom width. Figure 2 shows influence of control factors on kerf taper ratio.

As abrasive waterjet pressure increases, the kerf taper ratio decreases since kinetic energy of the jet increases. It is clear from the graph that kerf ratio obtained for abrasive waterjet pressure of 96 MPa is lesser than that obtained for 72 MPa and kerf taper ratio for 120 MPa is still lesser than that obtained for 96 MPa.Therfore, kerf taper ratio is inversely proportional to abrasive waterjet pressure.

As traverse speed of nozzle increseses,kerf taper ratio increases because exposure time of the jet over the workpiece decreses.Hence in each set of 9 runs, this pattern is observed in the graph. For traverse speed equal to 150 mm/min, kerf taper ratio is minimum.

As stand-off distance increases, kerf taper ratio increases because diverging tendency of the jet increases and effective diameter of the jet increases which reduces penetration ability. It is clear from the graph that kerf taper ratio is minimum for stand-off distance of 2 mm for each set of 9 runs.

Abrasive waterjet pressure is found to be most significant control factor which will be cleared by analysis of variance (ANOVA).

TABLE III
ANOVA for Top Width

Factor	Sum of Squares	Degrees of Freedom	Mean Squares	Variance Ratio	Percentage Contribution
Waterjet Pressure (A) MPa	9.2085	2	4.6042	37.63	91.83
Traverse Rate (B) mm/min	0.5746	2	0.2879	2.34	5.73
Stand-off Distance (C) mm	0.2447	2	0.1223	1	2.44
Total	10.0278	6			100

TABLE IV
ANOVA FOR BOTTOM WIDTH

Factor	Sum of Squares	Degrees of Freedom	Mean Squares	Variance Ratio	Percentage Contribution
Waterjet Pressure (A) MPa	6.3169	2	3.1584	30.6046	87.45
Traverse Rate (B) mm/min	0.7001	2	0.3500	3.3921	9.69
Stand-off Distance (C) mm	0.2064	2	0.1032	1	2.86
Total	7.2254	6			100

TABLE V
ANOVA FOR KERF TAPER RATIO

Factor	Sum of Squares	Degrees of Freedom	Mean Squares	Variance Ratio	Percentage Contribution
Waterjet Pressure (A) MPa	0.05265	2	0.02632	2.009	46.74
Traverse Rate (B) mm/min	0.03379	2	0.01689	1.2893	29.99
Stand-off Distance (C) mm	0.02620	2	0.0131	1	23.25
Total	0.11264	6			100

From the ANOVA for top width, bottom width and kerf taper ratio, is clear that the percentage contribution for abrasive waterjet pressure is higher than that for traverse speed and stand-off distance.

Hence, abrasive waterjet pressure is most significant control factor influencing kerf geometry.

4.2. *Conformation Test*

In order to validate the predictive models for top width, bottom width and kef taper ratio, experiments were conducted to compare the predicted values against experimental values. The results are tabulated below:

TABLE VI
COMPARISON OF EXPERIMENTAL AND PREDICTED VALUES FOR KERF GEOMETRY

Control Factors			Experimental Values			Predicted Values		
T	P	SOD	Top Width	Bottom Width	Kerf Ratio	Top Width	Bottom Width	*Kerf Ratio*
162	96	4.0000	2.9037	2.016	1.440327381	2.5027	1.8987	1.318112
167	120	3.0000	3.3594	2.738	1.3037	3.8798	3.1296	1.239711
275	72	2.0000	1.083	0.755	1.434437086	1.2418	0.8658	1.43428

The predictive models were developed for certain range of parameters so in order to judge the accuracy of models, experiments were conducted by taking random values of control factors and the predictive values at the same values of control factors were calculated and tabulated as follows:

TABLE VII
ERROR ESTIMATION

	Top Width	Bottom Width	Kerf Ratio	Top Width	Bottom Width	Kerf Ratio
	$Bias = \frac{Experimental - predicted}{Experimental} \times 100$			$Absoulute = \left\| \frac{Experimental - predicted}{Experimental} \right\| \times 100$		
	0.1381	0.0582	0.0849	0.1381	0.0582	0.0849
	-0.1549	-0.1430	0.0491	0.1549	0.1430	0.0491
	-0.1466	-0.1468	0.0001	0.1466	0.1468	0.0001
Average Error→	-0.0545	-0.0772	0.0447	0.1465	0.1160	0.0447
%	-5.4480	-7.7198	4.4681	14.6547	11.6000	4.4680

This shows that bias as well as absolute errors are less than 15 %.

V.CONCLUSION

During the present course of work, extensive experiments were carried out including specimen preparation of laminate consisting of aluminium as a metal and polyester as a polymer. Cutting of laminates by varying control factors such as abrasive waterjet pressure, traverse speed and stand-off distance. All observations were analysed to develop predictive models for kerf geometry.

The following points are observed:

1. As abrasive waterjet pressure increases, kerf width increases but kerf taper ratio decreases.
2. As traverse rate of nozzle increases, kerf width decreases but kerf taper ratio increases.
3. As stand-off distance increases, kerf width decreases but kerf taper ratio increases.
4. Abrasive waterjet pressure is most significant control factor affecting kerf geometry in present study.

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