Acrylic based Experimental Analysis of Abrasive Water Jet Pocket Milling

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***Abstract*— For difficult-to-machining materials abrasive water jet machining (AWJM) process is used for machining. AWJM can also be used for various machining operations like drilling, cutting, turning, milling, etc. Experimental investigations in the Abrasive Water Jet Pocket Milling (AWJPM) in different materials like aluminium, glass, titanium, alloy steels, etc. are done by many researchers. They have tried to understand the effect of input parameters like water jet pressure, standoff distance, traverse rate, abrasive mass flow rate, jet impact angle, step-over distance, abrasive mesh size, machining time, etc. on the output parameters such as depth of cut, undercut, material removal rate (MRR), surface roughness (R_a), kerf geometry, etc. The objective of this work is to conduct experimental investigation in AWJPM in an acrylic material. The input parameters such as standoff distance, step-over size, traverse speed and abrasive flow rate are used study their effect on depth of cut and MRR. The L_9 orthogonal array is used for conducting experimentation. ANOVA analysis is used to determine the important parameters in AWJPM. It is also observed that standoff distance is most significant in achieving higher depth of cut and material removal rate. The formation of undercut is also demonstrated in this paper.**

Keywords*— MRR, Abrasive Water Jet, Abrasive Water Jet Pocket Milling, Garnet Abrasive, Acrylic, Orthogonal array, ANOVA.

I. INTRODUCTION

AWJM is commonly employed in industries for machining difficult-to-machine materials like glass, ceramics, composites, etc. (Fig. 1). In AWJM, a small stream of fine abrasive particles is mixed with water and accelerated at high velocities through an orifice of pressures normally in excess of 130 MPa (Fig. 2) [1]. Material removal occurs due to erosion caused by the impact of abrasive particles on the work surface. The motion of the cutting head in AWJM is controlled by a CNC controller through a CAD model [2]. No heat affected zone, low machining force on the work surface and ability to machine wide range of materials have increase the use of AWJM over other machining processes. AWJM can be used in a variety of applications such as drilling, polishing, turning, paint removal, cleaning, milling, etc.

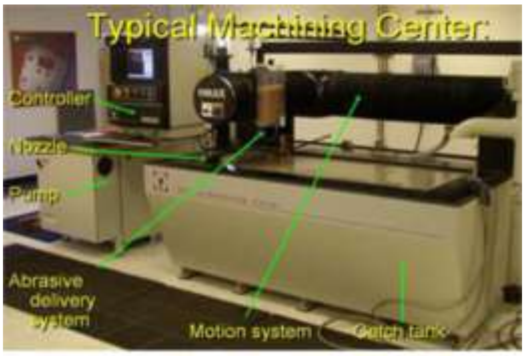


Fig 1: Typical AWJM center (www.omax.com)

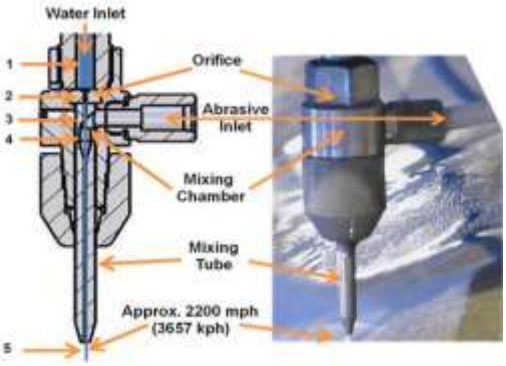


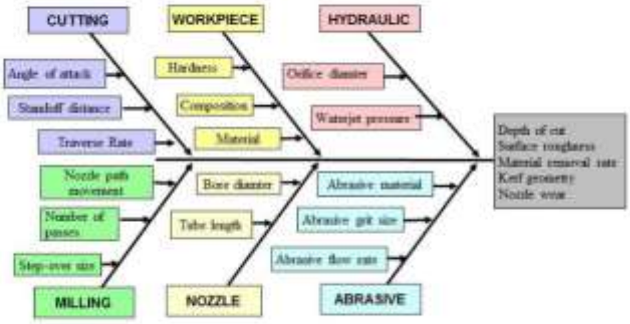
Fig 2: Schematic of the nozzle arrangement in AWJM (www.wardjet.com)

II. ABRASIVE WATER JET MILLING (AWJ MILLING)

AWJ milling uses a traditional AWJM system with high pressure water (typically upto 200 MPa) along with abrasive particles (usually garnet) to cut edges, slots, holes, pocket milling, etc. If the depth of cut is controlled during the milling process, then it is known as pocket milling. The process parameters in AWJPM are broadly classified into six categories namely (i) Hydraulic parameters: pump pressure, orifice diameter and water flow rate (ii) Mixing chamber and acceleration parameters: focus nozzle diameter and focus nozzle length (iii) Cutting parameters: traverse rate, stand-off distance and impact angle (iv) Abrasive parameters: abrasive flow rate, abrasive particles diameter, abrasive particle shape, abrasive and particle hardness (v) Work piece parameters: composition, material and hardness (vi) Milling parameters: nozzle path, number of passes and step-over size (Fig. 3). In abrasive water jet pocket milling (AWJPM), the water jet doesn't allow to pass all the way through the workpiece.

During AWJPM, the nozzle is allowed to move in step-over format (raster path) (Fig. 4). Raster path is a path in which the high pressure abrasive water jet moves in parallel direction, with 90˚ bends at the ends (Fig. 4). The amount of material removed can be precisely controlled if the process parameters are optimized in AWJPM. Researchers also used AWJPM for finishing a component accurately using a suitable mask [3]. The depth of cut in AWJPM is determined by the number of passes that the jet makes over the workpiece and also by varying the process parameters like water jet pressure, standoff distance, traverse rate, abrasive mass flow rate, step-over distance, abrasive mesh size, machining time, etc. AWJPM has many advantages over conventional milling because it is easy to machine low machinability (difficult-to-machine) materials, high versatility, flexibility, minimum stress, minimum cutting forces on the workpiece, environment friendly, no tool changing, minimum burr formation, etc. The intrinsic properties of the workpiece are intact even after machining because of no thermal distortion when compared to conventional milling [2].

Fig 3: Fish bone diagram of AWJPM



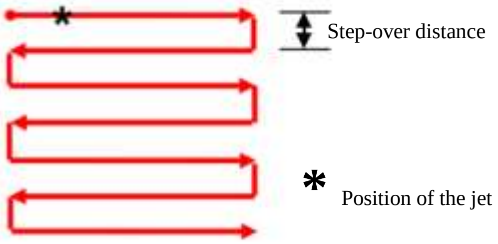


Fig 4: Schematic diagram showing the step-over format (raster path) in AWJPM [4]

III. LITERATURE REVIEW

Shipway et al. [5] studied the surface characteristics of AWJPM on titanium alloy (Ti6A14V). They observed that the material removal rate is about 55 % lower at higher traverse speeds (0.01 m/s) with smaller grit size (80 mesh) than that of with the larger grit size (200 mesh). They have also observed that increase in traverse rate results in the reduction in surface waviness, while using both grit sizes of abrasives (garnets). The reduction is being most significant while using larger grit size of the abrasives. They have also observed that the material removal rate was high at the lowest traverse rate (0.003 m/s) and decreased rapidly with increased traverse rate. From their studies, it is observed that increase in the water jet pressure for different traverse rate results in an increase in the surface waviness and also the water jet pressure has significant influence on the surface waviness at the lower traverse rate than that of the higher traverse rate.

Fowler et al. [6] have carried out AWJPM in titanium alloy (Ti6Al4V) to study the effects of different abrasive particle (white aluminium oxide and brown aluminium oxide, garnet, glass beads and steel shots) shape and hardness. They have observed that the ratio between the hardness of the workpiece and the abrasive particle is more significant than that of abrasive particle shape. They have also observed that increase in the material removal rate and surface roughness with the increase in the abrasive particle hardness. They have observed that among the different input process parameter, traverse rate is found to be more significant for material removal rate for different abrasives. They have also found that shape factor and particle hardness does not have significant effect on the surface waviness.

Kong et al. [7] have carried out AWJPM in Ni-Ti shape memory alloy and observed that the AWJPM is having a better control over depth of cut than that of the plain water jet pocket milling (PWJPM) process. They have found that the surface generated by PWJPM is relatively smooth compare to AWJPM, except the existence of some locally deformed and pulled-out spots (e.g. craters) during the first milling pass. However, with the increase in the number of pocket milling passes (3 passes) more craters with higher surface roughness were observed. They have also observed larger craters with higher surface roughness and with lower erosion resistance with inclination of the nozzle at 75˚. They have also found that the material removal occurs pre-dominantly by micro-abrasion mechanism, which involves grooving and ploughing.

Pal and Tandon [8] have carried out AWJPM in six different materials such as aluminium 6061, aluminium 2024, brass 353, titanium, Ti6Al4V, stainless steel AISI 304 and tool steel. They have found that the machinability index and mechanical properties of the material plays an important role in establishing pocket milling time and surface roughness (R_a). They have varied the depth of cut to estimate the corresponding pocket milling time. For higher depth of cut, milling time is found to be increasing; correspondingly the surface roughness is also increased. It is observed that, pocket milling time increases non-linearly as the depth of cut increases due to loss of energy of jet. Similarly, they have also observed with the increase in the standoff distance. For low machinability index materials like titanium and stainless steel have non-linearity effect due to the divergence of the jet stream.

Wang et al [9] carried out AWJPM in glass and classified the machined surface into four different zones namely (i) opening zone (ii) steady cutting zone (iii) unsteady cutting zone and (iv) finishing zone (Fig. 5). They observed that the formation of the opening zone is due to the impact of the jet (viscous flow) on the top surface of the material. The formation of steady cutting zone is due to the primary erosion (turbulent flow) during the penetration of the jet into the material. The formation of unsteady cutting zone is due to the secondary erosion (deformation wear) as a result of transition or laminar flow of the jet at the downstream (Fig. 6). The formation of finishing zone is due to the accumulation of the low-energy solid particles (abrasives), which travel with water jet on the channel surface and causes sweep type micromachining.

Fig 5: Four erosion zones during the channel formation [9]

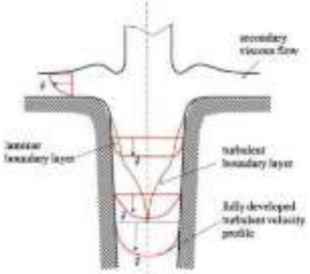


Fig 6: Schematic of the flow development during jet impact [9]

They have also observed the formation of bulges at the bottom of the channel and also at the corners/walls with higher traverse rate (Fig. 7). This may be due to the force induced on the workpiece by the acceleration /deceleration of the moving nozzle during the changes in the jet direction. They have also observed that low step-over distance, high traverse rate and low standoff distance result in equidistant lay (parallel grooves) marks and saw tooth waves on the machined surface. They have also studied the effect of tilting the nozzle head at different angles 45°, 60° and 75°. They observed that the increased jet impact angle (75°) and the low traverse rate (e.g. 10 mm/s) result in lower wall inclination angle. They finally concluded that the milling depth and machined surface quality can be controlled through the proper selection of input process parameters.

From the literature review, it is found that no information is available about the effect of input process parameters on output process parameters in acrylic material, moreover the effect of undercut formation is not widely discussed. Therefore, in this work, experimental investigations are carried out to study the effect of AWJPM input parameters on depth of cut and material removal rate.

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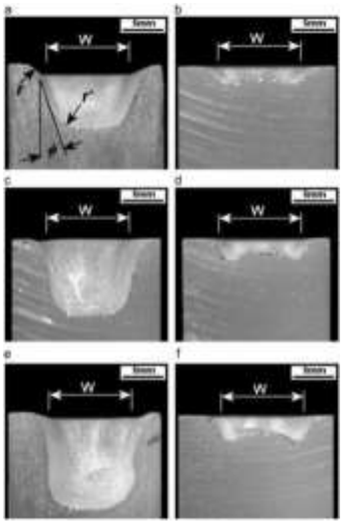

Fig 7: Cross-sectional view of the channels at different jet impact angle and traverse rate [9]

IV. EXPERIMENTAL DETAILS

The following section gives the details about workpiece material, machine and experimental design

A. *Material*

In this investigation, the acrylic is used as a workpiece material. The following Table I give the details of properties of the workpiece.

TABLE I: PROPERTIES OF ACRYLIC MATERIAL

Properties	**Values**
Density	1180 (kg/m^3)
Tensile strength	37 to 73 (MPa)
Tensile elongation	2.4 to 5.2 (%)
Flexural strength	37 to 137 (MPa)
Compressive strength	97 to 124 (MPa)

The transparent acrylic material is selected in this work in order to study the effect of different AWJPM process parameters on kerf geometry, undercut, depth of cut, etc. The workpiece material is of dimension 300×300×18 mm is placed on the grill of the AWJ machining center and it is clamped using quick action gripers. The dimension of each pocket is 20×12 mm. The raster path was chosen for all the experiments (Fig. 4) with different step-over sizes (Table 2). The abrasive material used during this work is garnet of size #85 mesh.

Fig 8: Photograph of the AWJPM workpiece

TABLE II: PROCESS PARAMETERS CHOSEN AT DIFFERENT LEVELS

S. No.	**Variable Parameters**	**Levels**		
		Low	***Medium***	***High***
1	Standoff Distance [SOD] (mm)	5	6	7
2	Step - over [SO] (mm)	0.2	0.3	0.4
3	Traverse Rate [TR] (mm/min)	2500	3000	3500
4	Abrasive Flow Rate [AFR] (kg/min)	0.22	0.32	0.42

B. *Machine details*

OMAX make Abrasive Water Jet Machine (model no. 2626 OMAX) is used for experimentation. The machine has high pressure, electrically driven, variable speed and positive displacement pump. The table size is 1168 x 787 mm. X-Y cutting travel is 737 x 660 mm and Z-axis travel is 203 mm. Accuracy and repeatability of the above machine are ± 0.025 mm. The mixing tube diameter of 0.76 mm and orifice diameter of 0.35 mm are used during this work.

Fig 9: Photograph of AWJ machining setup facility

C. *Experimental design*

The experiments were performed as per the L_9 orthogonal array and the responses (depth of cut and material removal rate) is measured using TESA IP67 digital vernier caliper with least count of 0.01 mm. The MRR is calculated using volume and machining time for each pocket. The input parameters considered in this work are traverse rate, step-over, standoff distance and abrasive flow rate and each of the above parameters is varied over three levels such as low, medium and high, while the pressure is kept statistically constant at 138 MPa (Table. II). The output parameters considered in this study are depth of cut and material removal rate. The collected data was then computed using ANOVA TM software to find the percentage contribution of each input parameter and also to identify the significant process parameters (Table IV and Table V). Response graphs for the output parameters are also observed using ANOVA TM (Fig. 11 and Fig. 12).

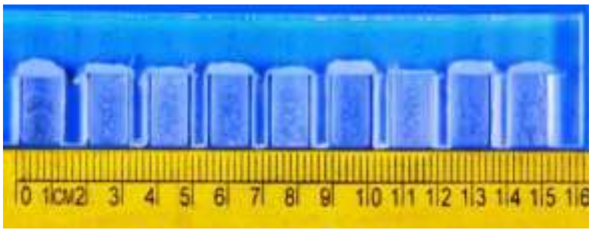

Fig 10: Top view of the machined workpiece

TABLE III: EXPERIMENTAL RESULTS

S.NO	INPUT PROCESS PARAMETERS				OUTPUT PROCESS PARAMTERS	
	Standoff Distance [SOD] (mm)	**Step-over [SO] (mm)**	**Traverse Rate [TR] (mm/min)**	**Abrasive Flow Rate [AFR] (kg/min)**	**Depth Of Cut (mm)**	**Material Removal Rate (mm^3/min)**
1	5	0.2	2500	0.22	9.11	2062.07
2	5	0.3	3000	0.32	7.86	2656.90
3	5	0.4	3500	0.42	6.88	3175.38
4	6	0.2	3000	0.42	6.51	1531.18
5	6	0.3	3500	0.22	5.67	1972.17
6	6	0.4	2500	0.32	4.89	2133.82
7	7	0.2	3500	0.32	5.10	1222.80
8	7	0.3	2500	0.42	4.10	1336.44
9	7	0.4	3000	0.22	3.73	1689.06

TABLE IV: ANOVA RESULTS OF DEPTH OF CUT

Source	Pool	DF	S	V	F	S'	ρ
SOD*	-	2	2257539	1128769	108.49	2236732	70.09
SO*	-	2	794407	397203	38.17	773600	24.24
TR	-	2	118261	59130	5.68	97454	3.05
AFR	Y	2	20807	10403	-	-	-
(e)	-	2	20807	10403	-	83230	2.61
Total	-	8	3191016	398877	-	-	-

TABLE V: ANOVA RESULTS OF MATERIALREMOVAL RATE

Source	Pool	DF	S	V	F	S'	ρ
SOD*	-	2	20.387	10.193	482.49	20.345	80.73
SO*	-	2	4.581	2.29	108.43	4.539	18.01
TR	Y	2	0.042	0.021	-	-	-
AFR	-	2	0.189	0.094	4.48	0.147	0.58
(e)	-	2	0.042	0.021	-	0.169	0.67
Total	-	8	25.201	3.15	-	-	-

SOD – Standoff Distance (mm)
SO – Step-over (mm)
TR – Traverse Rate (mm/min)
AFR – Abrasive Flow Rate (kg/min)
e – Error
Y – Pooled Variable
* – Significant Parameter
DF – Degree of Freedom
S – Sum of squares
V – Variance
F – F ratio
S' – Pure sum of squares
ρ – Percentage contribution (%)

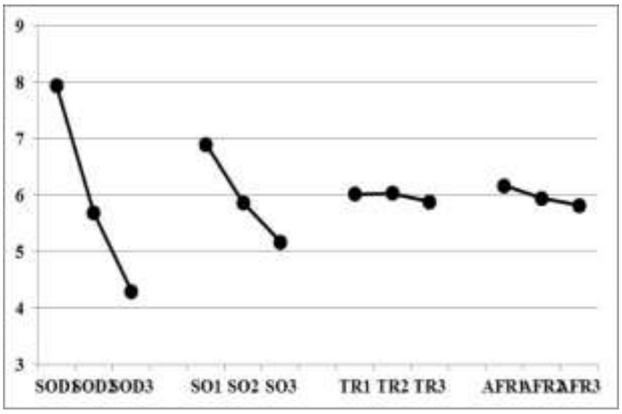

Fig 11: Response graph of depth of cut

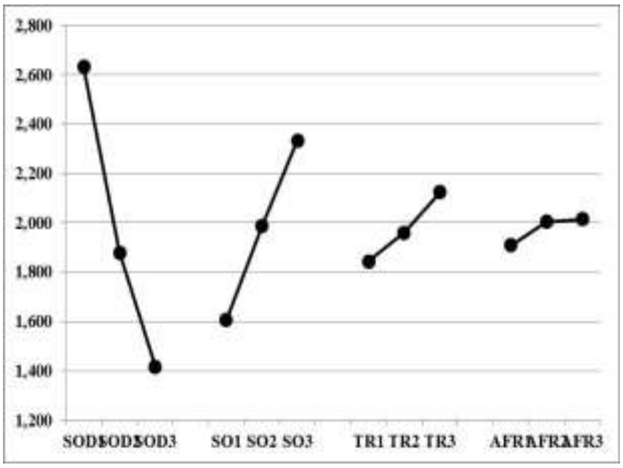

Fig 12: Response graph of material removal rate

SOD – Standoff Distance (mm)
SO – Step-over (mm)
TR – Traverse Rate (mm/min)
AFR – Abrasive Flow Rate (kg/min)
1 – Low level
2 – Medium level
3 – High level

V. RESULTS AND DISCUSSIONS

This section gives the details of the input, output parameters considered in this work and the analysis of the results.

A. *Depth of cut*

Fig. 13 shows the AWJPM surface as per L_9 orthogonal array. From the ANOVA table (Table IV), it is observed that the standoff distance and step-over distance are the most significant parameter in achieving higher depth of cut with 90% confidence level. The traverse rate and abrasive flow rate are not found to be significant for achieving higher depth of cut. From the response graph (Fig. 11), it is found that depth of cut varies inversely with standoff distance, step-over distance and abrasive flow rate. However change in traverse rate doesn't vary the depth of cut considerably. Due to the large waviness at the channel bottom surface, surface roughness was not evaluated quantitatively in this study. Fig. 14 shows the traced image of the AWJPM workpiece (front view). From fig.14 it is observed that the 1st and 9th combination in L_9 orthogonal array have higher and lower depth of cut respectively (Table III).

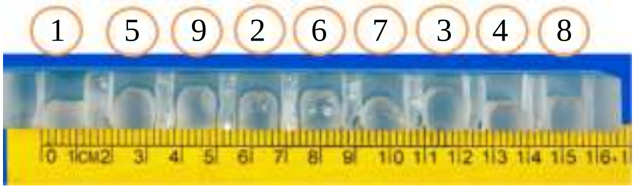

Fig 13: Front view of the workpiece

Fig 14: Traced front view of the workpiece

B. *Material removal rate*

From the ANOVA table (Table V), it is observed that the standoff distance and step-over distance are the most significant parameters in achieving higher material removal rate with 90% confidence level. The traverse rate and abrasive flow rate are not found to be significant for achieving higher material removal rate. From the response graph (Fig.12), it is found that material removal rate varies inversely with standoff distance and varies directly with step-over distance and traverse rate. However, change in abrasive flow rate doesn't vary material removal rate considerably.

C. *Undercut*

After pocket milling, the workpiece material is cross-sectioned to study the undercut formation. Mostly, the formation of undercut is found to be at the beginning of the jet-path (Fig 15, Fig. 16 and Fig. 17). The main factor which controls the undercut is found to be water pressure [4]. This is formed due to loss of energy of the water jet after reaching the certain depth and gets deflected and also causes sweep type micromachining at the end of the jet.

Fig 15: Cross section view of the pocket showing undercut

Fig 16: Close up view of the undercut

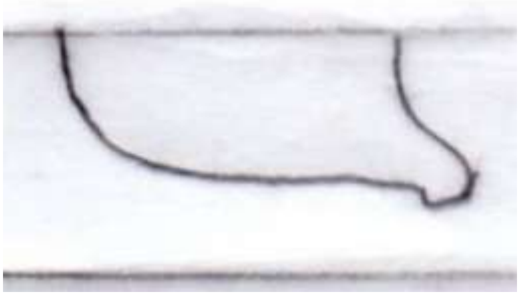

Fig 17: Traced close up view of the undercut

VI. CONCLUSION

This work aims to determine the significant input parameters in AWJPM for achieving higher depth of cut and material removal rate in acrylic. From the experimental results and ANOVA, it is found that standoff distance and step-over distance are the most significant parameter for the controlling depth of cut and material removal rate. However, traverse rate and abrasive flow rate has minimal effect on depth of cut and material removal rate. An undercut formation is also observed during AWJPM. The controlling of the undercut formation is also reported. However, complete elimination of undercut and interaction effects within the process parameters is beyond the scope of this work. This leaves a lot of scope for future study.

VII. ACKNOWLEDGMENT

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