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Role of Process Parameters on Pocket Milling with Abrasive Water Jet Machining Technique

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***Abstract*—**Abrasive Water Jet Machining is an unconventional machining process well known for machining hard to cut materials. The primary research focus on the process was for through cutting and a very limited literature is available on pocket milling using AWJM. The present work is an attempt to use this process for milling applications considering a set of various process parameters. Four different input parameters, which were considered by researchers for part separation, are selected for the above application, i.e., abrasive size, flow rate, standoff distance and traverse speed. Pockets of definite size are machined to investigate surface roughness, material removal rate and pocket depth. Based on the data available through experiments on SS304 material, it is observed that higher traverse speeds gives a better finish because of reduction in the particle energy density and lower depth is also observed. Increase in the standoff distance and abrasive flow rate reduces the rate of material removal as the jet loses its focus and occurrence of collisions within the particles. ANOVA for individual output parameter has been studied to know the significant process parameters.

***Keywords*—**Abrasive flow rate, surface finish, abrasive size, standoff distance, traverse speed.

I. Introduction

ABRASIVE Water Jet Machining (AWJM) is one of the commonly used unconventional machining processes, where highly pressurized water allowed to flow through an orifice gets converted to a very high velocity jet. The high velocity jet when mixed with abrasives and focused to hit a target surface enhances the jet cutting ability. The process can be used to cut a wide variety of materials ranging from soft to hard like titanium, inconel, etc. [1]. Some of the major advantages of the process include minimum heat affected zone, increased machining capability and more flexibility with low cutting forces. The absence of electrical and thermal energies during machining leads to negligible material defects occur on the product/component unlike any other unconventional machining process. Originally abrasive water jets are used for linear and shape cutting of difficult to cut materials [2]. Later the process has been attracted in the turning, small holes drilling and very recently for controlled depth blind features too.

AWJM is a very complex process influenced by several process parameters ranging from hydraulic, dynamic, abrasive, cutting etc. where some of them can be controlled. Parameters like abrasive flow rate, traverse speed, standoff distance and water jet pressure are dynamic and are controllable parameters. Efforts were put by researchers to understand the process and improving its performance. The basic phenomenon of material removal mechanism in AWJM is erosion [3] and it involves micro cutting; plastic deformation [4], [5] where a generic model has been developed considering the entire material removal process as ‘cutting wear’ mode and deformation mode. Cutting wear happens at low impact angles and deformation wear occur at high impact angles. Thick materials are characterized after machining as two types of textures, top smooth texture and the bottom rough texture [6].

Striation formation is a major limitation of the AWJM, which is a characteristic of the process. This is due to the fact in the process, that the jet diverges once it ejects from the mixing tube and this deviation increases with traverse speed. The particle distribution, dynamic characteristics and the machining system vibrations also lead to the striations formation [7]-[9]. Irregular surfaces are obtained while machining at low traverse speeds [10]. Prediction of fluctuations in the local curvature of the cutting front based on the model developed [11] are an inherent property of the process and cannot be eliminated even after controlling them very precisely. Based on the available literature, it was observed that AWJM is a well-defined process for through cutting the creation of blind features has received little attention.

A preliminary investigation for milling using abrasive water jets through experiments for understanding the influence of abrasive type and size on surface finish is attempted and later milling of isogrid structures with the use of a masking material is also done [12], [13]. A study on the role of grit embedment with process parameters, material removal mechanism while milling titanium using number of passes, effect of abrasive shape and hardness on the workpiece is also studied [14]-[16].

The important parameters for estimating the quality of features in milling with AWJM are depth and surface roughness. Modeling of AWJ milling is difficult because of continuously varying dynamic variables. Parameters like pump pressure, traverse speed, abrasive flow rate, and jet impact angle significantly affect the efficiency of AWJ milling and the geometrical characteristics. A real time control of process parameters in milling is a challenging problem which has been

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not addressed by researchers as on date. The focus of the paper is to investigate experimentally, the influence of traverse speed, abrasive flow rate, abrasive size and standoff distance on surface roughness (Ra), material removal rate (mrr) and pocket depth during milling with AWJM and their significance has been observed through ANOVA technique.

II. Experimentation

A. Rationale of the Process

Blind pocket milling has major applications in the areas of automobiles, aerospace, defense sectors, where in particular the work piece is hard to be machined and without compromising the strength the weight of the component is to be reduced.

B. Experimental Setup

Fig. 1 shows the schematic of the experimental setup. A fixture (Fig. 2) to accommodate a workpiece of size 30 mm x 30 mm x 10 mm is fabricated and fixed to bed of the machine. SS304 is a standard material which is resistant to wear and corrosion is chosen for experimentation. A CNC controlled AWJM center (Model No. 2626, OMAX, USA make) which can generate pressures up to 340 MPa. A raster tool path as indicated in Fig. 3 with a step over of 0.4mm (approximately half the diameter of jet) is considered. Due to the dynamics physics of the machine, the traverse rate of the machine decelerates in the areas where the jet changes its direction. This deceleration results in material removal mechanism to change from milling to cutting which in turn increases the localized material removal rate. It is observed that the depth at the corners increases greatly because of the above phenomenon. Various traverse paths are tried and the raster path gives a better surface where a sample pocket surface is shown in Fig. 4.

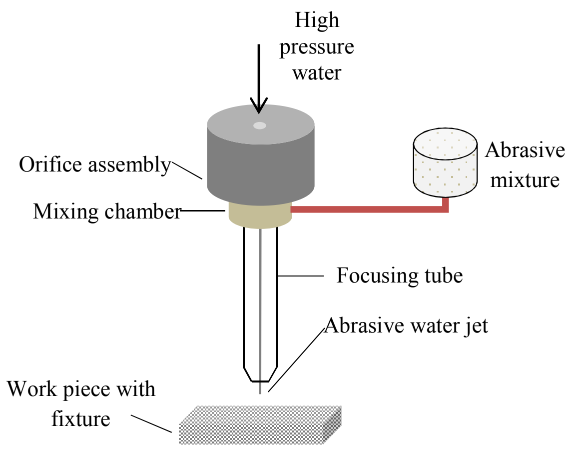

Fig. 1 Schematic of the experimental setup

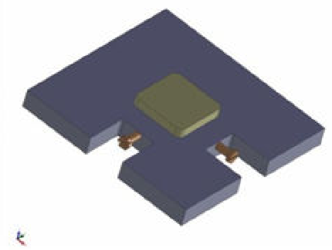

Fig. 2 Work holding fixure

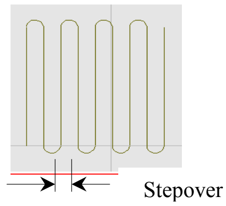

Fig. 3 Traverse path direction

Fig. 4 Sample pocket milled surface

III. ANOVA and Measurements

A. Design of Experiments (DOE) and Process Parameters

A full factorial experimental set consisting of traverse speed, abrasive flow rate, abrasive size and standoff distance as process parameters considering each at 3-levels with all possible combinations leading to total of 81 experiments is used. This DOE helps us for conducting experiments in a more systematic way. The process parameters range is specified in Table I. These ranges are chosen based on machine limiting conditions, resources availability and the available literature. Garnets are the abrasives used in the present experiments having a specific gravity of 3.90 and bulk density of 2.48 kg/mm^3. All the experiments are conducted at a constant pressure of 241.3 MPa using a fresh orifice with 0.32mm dia. along with a 0.762mm dia. focusing tube.

TABLE I
Range of Process Parameters

Parameter	Range of values
Traverse Speed (mm/min)	3000, 3500, 4000
Abrasive Mesh Numbers	80, 120, 160
Standoff distance (mm)	3, 4, 5
Abrasive flow rate (kg/min)	0.27, 0.38, 0.49

B. Measurements

All 81experiments are conducted at 90^0 jet impingement angle only. The specimen is weighed before and after the experimentation. The ratio of volume difference to total cutting time gives the volumetric material removal rate. Surface roughness (Ra) is measured with a Rugosurf 10G, surface analyzer having a tolerance level of 0.01 microns. The pocket depth is measured with a height gauge. An average of the readings taken at various locations on the cut surface gives the pocket depth.

C. Statistical Analysis

Table II gives a sample set of experimental data consisting of process parameters and corresponding output parameters like mrr, Ra, and depth. Statistical analysis of the experimental data has been carried to understand the significance of process parameters. On carrying out ANOVA analysis, it is found that interactions are also significant along with individual parameters. Considering the parameters having P-values less than 0.05, the abrasive size is the most significant process parameter followed by traverse speed and standoff distance. The data analysis reveals that abrasive flow rate is not a very significant process parameter.

While carrying ANOVA analysis for surface roughness, standoff distance is the most significant parameter followed by particle size and traverse speed. In the current scenario also the abrasive flow rate is the least significant process parameter. For pocket depth, particle size and traverse speed play a very significant role followed by standoff distance and the significance of abrasive flow rate is the least when compared to other parameters.

IV. Results and Discussion

The present study is an attempt to investigate and explain the influence of parameters for milling applications by AWJM process. As mentioned above the process is influenced by a large set of process parameters and the effects of individual process parameter are explained as follows:

A. Traverse Speed

In AWJM, traverse speed plays an important role in the material removal process. This decides the local exposure time, in which the abrasive water jet acts on the work material. Figs. 5-8 illustrate the effect of traverse speed on surface roughness; material removal rate and depth with other process parameters. At low speeds the material removal is mainly by cutting resulting in a poor surface due to the damping effect of the abrasive particle on the surface. In this case, more interaction time of the jet with work surface gives higher material removal. At higher speeds, energy density of the particle reduces while impacting the surface leading to reduced depths and improves surface finish to some extent. In this case, the kinetic energy transferred to the work piece by the abrasive water jet is inversely proportional to the traverse rate.

B. Influence of Standoff Distance

The distance between the nozzle tip and work surface termed as stand-off distance (SOD), is one of the process parameter to be considered. If the SOD is low, the abrasive flow is damped or decelerated by the target surface leading to a poor surface and increased material removal rate. As the SOD is increased, the jet diameter increases which reduces the energy density of the jet. The reduction in this energy density generates more random peaks and valleys on the pocket surface creating a poor surface.

TABLE II
INPUT AND OUTPUT PARAMETERS

Exp. No	Ts	AFR	Abr. mesh	SOD	MRR	Ra	Depth
1	3000	0.49	80	4	22.653	5.49	0.88
2	3500	0.49	120	5	22.221	4.42	0.76
3	3500	0.38	160	4	21.575	6.36	0.74
4	3500	0.38	80	4	22.224	5.23	0.74
5	3500	0.27	80	3	22.394	5.45	0.79
6	3500	0.38	80	5	22.427	5.01	0.71
7	3000	0.49	120	4	20.319	4.86	0.85
8	4000	0.38	80	3	22.202	5.05	0.61
9	4000	0.38	80	4	20.965	5.89	0.67
10	3000	0.27	80	5	22.258	5.40	0.85
11	3000	0.27	160	4	21.758	4.61	0.92
12	3000	0.49	160	4	21.866	7.00	1.02
13	3000	0.38	80	3	22.590	5.80	0.82
14	4000	0.49	80	4	22.223	4.39	0.64
15	3500	0.38	80	3	22.104	5.92	0.59
16	3500	0.49	120	4	22.058	4.68	0.75
17	4000	0.49	160	4	21.310	6.41	0.71
18	3500	0.27	160	5	21.189	6.28	0.79
19	3000	0.27	80	3	22.526	6.19	0.90
20	3500	0.27	120	3	22.357	5.26	0.83
21	4000	0.27	80	4	22.168	5.54	0.60
22	4000	0.27	120	3	21.744	5.65	0.65
23	4000	0.49	120	3	22.079	5.12	0.61
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76	4000	0.49	80	3	22.531	6.00	0.62
77	3500	0.27	120	5	22.440	4.99	0.76
78	3500	0.38	160	3	21.537	7.21	0.79
79	4000	0.49	160	5	21.246	5.27	0.66
80	3500	0.49	80	5	22.723	5.65	0.75
81	4000	0.49	120	5	22.288	5.23	0.59

MRR-mm^3/min, Ra-µm, Depth-mm

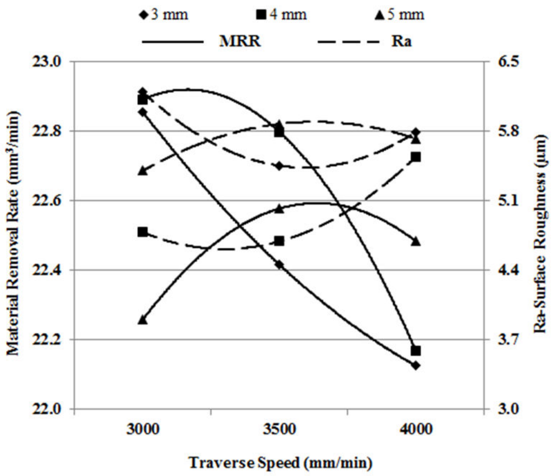


Fig. 5 Effect of standoff distance with traverse speed on mrr and Ra (80mesh, Pressure 241.3 MPa)

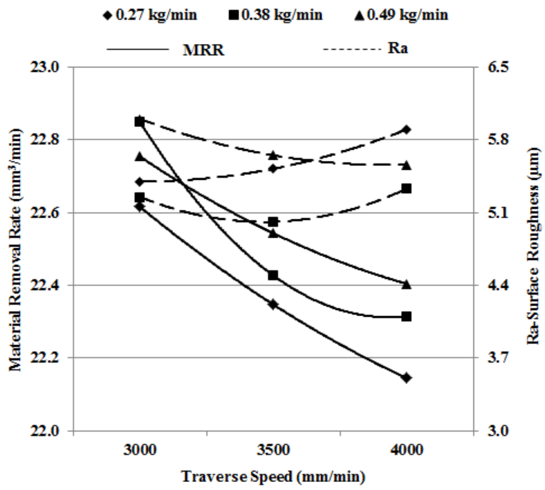


Fig. 6 Effect of AFR with traverse speed on mrr and Ra (80mesh, SOD 5mm, Pressure 241.3 MPa)

At SOD of 3mm, the surface roughness is more at low traverse speeds and on increasing the SOD to 4mm, the finish improves as shown in Fig. 5. Further increasing the SOD to 5 mm the surface deteriorates due to diversification of the jet. The decrease in material removal rate at 3mm is due to upward deflection of the jet. A higher mrr and better finish is observed at SOD of 4mm as the jet stabilizes with minimum fluctuations. It is observed that at SOD of 4mm the material removal is predominantly by cutting wear mode and on further increasing the SOD to 5mm the roughness increases. At this stage the mechanism shifts from cutting to deformation wear mode. Similar trends were observed while cutting coated steel sheets [17]; laminates [18], and cutting ceramics [9].

In general, SOD has more influence on the penetration depth than material removal rate which is also clearly observed that the rate of change in material removal is not very significant compared to the surface finish. This is due to the radial expansion of the jet yields a larger exposed area.

C. Effect of Abrasive Flow Rate (AFR)

AFR also has significant influence on the output, which is a function is a result of several effects, where it gives the number of particles involved in the process of mixing and cutting. Assuming no contact between the grains during the course of mixing and cutting, an increase in the AFR leads to a proportional increase in the depth of cut. This relation holds at low AFRs only.

At higher values of AFR, the particles collide with each other in the mixing chamber, acceleration in focusing tube and during cutting. Here, the limited kinetic energy of the water jet distributes over a large number of particles leading to reduction in the kinetic energy of the actual impacting individual particles. Observations made by earlier researchers revealed that the turbulence in abrasive water jet increases with increase in AFR. With increase in AFR, initially MRR increases and then decreases due to reduction in the abrasive flow velocity and at a particular value of AFR, any additional increase in abrasives does not contribute to any notable change in the material removal rate.

Fig. 6 shows that at low AFRs with traverse speed, say at 0.27 kg/min, the quantity of abrasives impinging the surface is less and the material removal mechanism is predominantly by deformation than cutting. At a given AFR, surface roughness increases with increase in traverse speed, while the material removal rate decreases. On increasing the AFR to 0.38 kg/min, better surface finish is observed than other AFRs. A further increase in the AFR to 0.49 kg/min results in a poor surface due to collision between the particles.

D. Role of Abrasive Size

The particle size and shape are also important in the machining process by AWJM. The larger the particle size more is the material removal rate or the depth since the kinetic energy of the particle increases, as plotted in Fig. 7. On the other hand the number of particles reduces with an increase in the diameter. As the mesh number increases or the particle size decreases, the surface finish initially improves with increase in the traverse speed and deteriorates. An 80 mesh abrasive gives higher material removal rate and a poor finish and a 160 mesh enhances the surface finish compared to 80 and 120 size mesh.

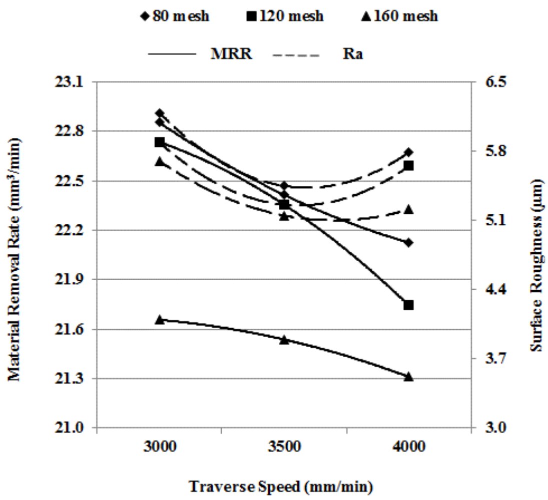


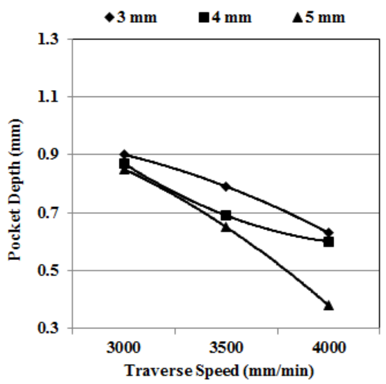
Fig. 7 Effect of abrasive size with traverse speed on mrr and Ra (AFR 0.27 kg/min, Pressure 241.3 MPa)

E. Influence of Process Parameters on Depth

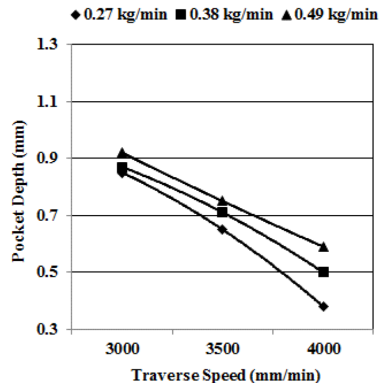
Apart from the material removal rate and surface roughness, pocket depth is also a significant parameter to be observed. The effect of SOD is shown in Fig. 8 (a) which depicts that the pocket depth decreases with an increase in the SOD. This is due to the fact that the jet loses its focus and improper machining takes place leading to decrease in pocket depth and increase in kerf width.

A higher AFR leads to increased number of impacting abrasive particles and higher kinetic energies. This further increases the role of abrasive particles in the mixing and cutting processes. As the AFR is increased, the depth of cut or the pocket depth increases, but decreases with the traverse speed as shown in Fig. 8 (b).

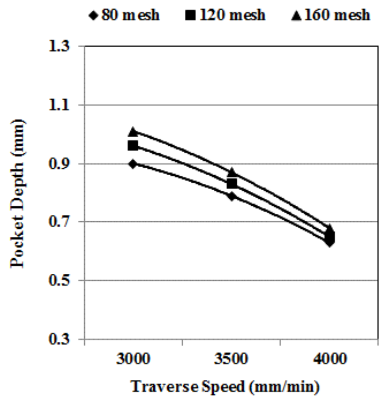
The pocket depth decreases with increase in the abrasive particle diameter. This could be due to less number of impacting particles and also the particle velocities. Irrespective of the size of the abrasive particle, the penetration depends on the indenting edges. The influence of abrasive size on the cutting process has higher probability of impact fracture leading to lesser material removal rate with traverse speed. This influence is clearly seen in the Fig. 8 (c).



(a)



(b)



(c)

Fig. 8 Influence of Effect of SOD (a), AFR (b) and abrasive size(C) with traverse speed on depth

V. CONCLUSIONS

The present work makes an attempt to investigate the feasibility of obtaining a milled pocket, so as to reduce the weight of the structure or component without losing its strength, as used in space and defense sectors, apart from other applications. Unlike in conventional abrasive water jet cutting, in milling applications traverse speed (jet and work interaction time) has been more influenced than any other process parameter. Higher traverse rates are very much essential for obtaining a better surface finish. While considering traverse speed with process parameters, an optimum traverse speed has to be chosen keeping the material removal rate and the pocket dimensions (this has been not addressed in this paper).

It has been observed that the mechanism of material removal is essentially cutting wear mode which is also predominant at SOD 4mm, AFR of 0.38kg/min. The size of the abrasive particle has not much say on the type of material removal mode either cutting or deformation. Increasing the traverse speeds shifts the material removal mechanism from cutting mode to deformation mode. Due to losing of jet focus at higher SODs, higher surface roughness and less material removal rates are observed. At higher AFRs, the surface roughness and material removal rate increases due to collisions between the particles. Coarse abrasive particles give a higher material removal rate and poor finish and a finer particle impact gives a better finish.

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