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Experimental Investigation and Analysis of Abrasive Water-Jet Machining Process

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Abstract - **The abrasive water-jet machining is an unconventional and eco-friendly technology used for industrial applications. This paper presents a comprehensive experimental investigation of the process, based on the material removal mechanism. The quality of surfaces machined using the process is investigated in detail. The results have indicated that surface roughness values (Ra in μm) vary between 3.5 and 5.5. The flow of abrasives, their speed and size influence quality of the machined surfaces. As the abrasive flow increases, the surface finish improves drastically. The optimum abrasive flow rate for obtaining the minimum surface roughness of 4.2 μm was corresponding to the maximum level of 7 g/s. This study has also indicated a possibility of applying abrasive water jet machining for fine polishing of machined surfaces, thereby validating the earlier investigations.**

Keywords: **Water jet Machining, Abrasive flow rate, Taguchi methodology, mechanism of removal, Surface finish and Optimization.**

I. INTRODUCTION

Abrasive water jet machining is an upcoming technology which is finding applications in cutting, pocket milling, turning and other machining operations for both ductile and brittle materials. The mechanism of material removal in ductile materials seems to be micro-cutting by the free flowing abrasive particles, accompanied by a large amount of plastic deformation [1]. In this machining process, high velocity water containing abrasive particles is used to cut different materials ranging from soft to hard and ductile to brittle materials. Hard abrasive particles are accelerated in the cutting head by a high speed water jet to achieve the material cutting. The cutting head consists of an orifice, a mixing chamber, an abrasive inlet and a focusing tube. Water at pressures up to 400 MPa is pushed to flow through an orifice with a diameter between 0.1 and 0.3 mm where a high-speed water jet is generated. The velocity of water jet is proportional to the square root of water pressure and usually reaches to a value of about 1000 m/s [2]. The high speed water jet suck the abrasive material through the abrasive inlet. The abrasive material mixes with the water in mixing chamber, which is placed downstream the orifice. Abrasive particles are accelerated in focusing tube which its diameter is usually twice of the orifice diameter. During the suction of abrasive particles, air is entered through the abrasive inlet, and droplets start to generate around the jet and abrasive parts are fragmented during the acceleration. The resulting high speed jet of abrasive particles, water and air form the tool in the machining. However in the case of the machining of very brittle materials such as ceramics, cemented carbides, glasses etc. the stress wave energy associated with the impact by the abrasive particles causes fracture [2–4] in addition to micro-cutting and gross plastic deformation. One of the main problems in modeling the total depth of cut achieved in the abrasive jet machining of brittle materials is to determine the stress wave energy as a percentage of the total energy [3,5]. Abrasive water jet machining is a well-established non-traditional machining process used for cutting difficult-to machine materials. This technique is especially suitable for very soft, brittle and fibrous materials. It is a machining process without much heat generation and the machined surface is virtually without any heat affected zone or residual stress. Different types of abrasives are used in abrasive jet machining like garnet, olivine, aluminum oxide (Al_2O_3), silica-sand, glass bead, silicon carbide (SiC), zirconium, etc. But a survey shows that 90% of the abrasive water jet machining is done using garnet [6]. The geometry cut by the abrasive water jet is characterized by the top width of cut, bottom width of cut, initial damaged width, initial damaged depth, etc. Effort should be given to minimize these parameters. The cut geometry depends on the type of abrasives and cutting parameters like abrasive jet pressure, standoff distance of the nozzle from the target, work feed rate, abrasive mass flow rate, etc. Efforts have been made to improve the cutting performance of the abrasive water jet. An addition of polymer to the water jet increases the jet penetration depth [7]. Hardness is an important character of the abrasives that influences on the cut geometry. The depth of penetration of the jet increases with the increase in hardness of the abrasives. But the depth of jet penetration greatly depends on the ratio of the hardness of the target materials and the hardness of the abrasives. Moreover, due to the anisotropic and non-homogeneous nature of composites, their machining behavior differs in many aspects from metal machining. In conventional machining processes notably drilling is the most frequently employed machining operation of composite materials. Due to the limitations of conventional machining processes, alternative techniques that utilize non-conventional energy sources for material removal such as electrical discharge machining, laser cutting, ultrasonic machining, water jet and abrasive water jet machining has drawn much interest and has been studied the feasibility of the processes [8]. Among these non-conventional machining processes, abrasive water jet machining is the only method used in industry today for trimming fibre reinforced composite materials as laser machining suffers from the problem of a large heat-affected zone, while EDM suffers from extremely low cutting rates [1]. The abrasive water jet machining process provides a single tool that is suitable for machining a wide range of composite materials. It is a non-contact, inertia-less and faster cutting process that offers some advantages like narrow kerf width, negligible heat affected zone, reduced waste materials and flexibility to machining process in different ways [9]. The use of the abrasive water jet machining process for through cutting is well developed but its use for the controlled-depth milling is still a subject for further investigations to enable better understanding of its particularities and material removal mechanism. The main challenges for performing controlled-depth abrasive water jet machining cutting reside in: (a) difficulty of predicting the jet footprint that is not only dependent on the jet plume characteristics (e.g. energy, mass flow of abrasives) but also on the kinematic parameters of the process (e.g. jet transverse speed of jet) as well on the characteristics of the workpiece material (e.g. hardness, toughness) [10]; (b) key characteristics of the water jet system (e.g. acceleration/ deceleration) that can influence the dwell (surface exposure) time as well as the jet tool path strategy; (c) interaction between the secondary (reflected) jet and the surface to be milled [3]. However, to enable the generation of complex surfaces using abrasive water jet machining milling, the critical step is to develop methods to predict the jet footprint. In abrasive water jet milling, the material removal is mainly caused by the impact of a multitude of abrasive particles at ultra-high velocities, while the water is impinging, the superficial damages (e.g. cracks, craters) generated by the first [4]. Nevertheless, before conducting simulations on the jet footprint as a whole, it is of critical importance to first generate and validate models on single-particle impact. Although the real abrasive water jet machining consists of a large number of irregular particles, the investigation on impact of a single particle of known shape onto a target will provide an insight into further finite element modeling to predict complete jet footprint. Models of jet particle impact have been developed using both analytical and finite element techniques. These models are based on a set of rules that describe the formation of the machined surface and do not take into account the properties of the materials, e.g. plasticity or material removal mechanism. Moreover, the key element (unit event) as discussed by the authors is the impact of a single particle but no data have been presented regarding the velocity calculation of the impacting particle, which governs the kinetic energy of the particles and hence the entire erosion phenomenon. Therefore, it is felt that an in-depth experimental investigation and analysis is to be performed to understand the characteristics of the water-jet machining process at various processing conditions. Therefore, this study aims at analysis of mechanism of material removal, selection of processing conditions based on the physics of the process as understood from the mechanisms, comprehensive experimentation and analysis of the results obtained quantitatively and qualitatively.

A.Mechanism of Material Removal

The process is associated with erosion, in which the surface profiles changes with deformation, fracture and material removal at collision of the particles. Erosion can be controlled by the sizes, the velocities, and the impingement angles of the solid particles. When the impingement angle is large, erosion of brittle materials normally is accompanied by brittle fracture. Meanwhile, when small particles collide onto a surface at small impingement angles, the surface profile changes without fracture as erosion of ductile materials. In order to finish a crack-free surface, the particles should be controlled to collide onto a surface at shallow angles and move horizontally at high velocities to keep high removal rates with kinetic energies. A schematic of the abrasive water jet machining process of glass is shown in Fig. 1.

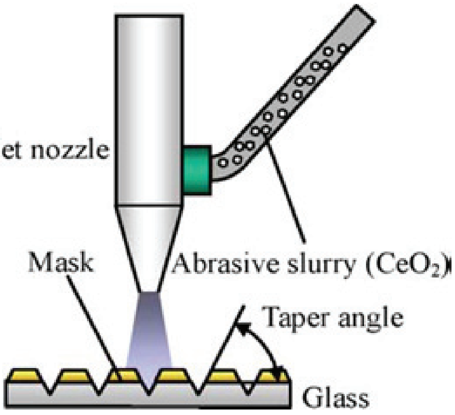


Fig. 1 Abrasive water jet machining of glass [3]

The polishing operation is a finishing method commonly used. The fluid polishing is here discussed to finish the micro grooves with the abrasive water jet. The jet nozzle traverses above the grooves to finish the grooves with supplying the abrasive slurry, see Fig. 2.

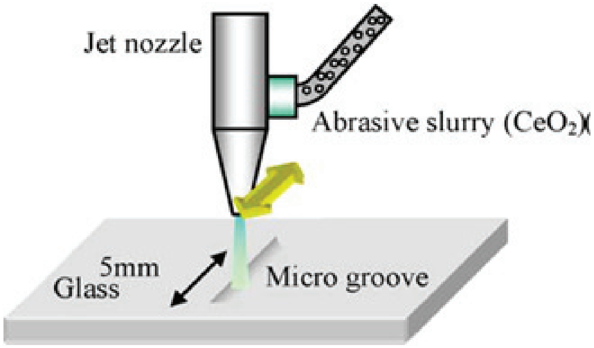


Fig. 2 Abrasive slurry for polishing operation [3]

In all these processing condition, the material removal takes place due to erosion of high-speed water jet when impacting on the workpiece. Similar process is an Abrasive Water Jet Machining where abrasive particles are added in the water jet in order to substantially improve the process performance, see Fig. 3. In this investigation, the water jet was used to produce tool electrodes since a smaller jet diameter can be obtained while keeping the machining performance still acceptable. Note that only small volume of the material have to be removed. As already anticipated in the early 1980's, manufacturing technologies of the future will have the ability of machining a variety of different materials in an energy effective way.

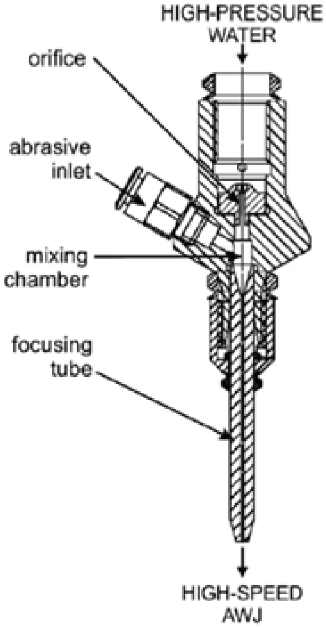


Fig. 3 Different parts of the cutting head used for supply of abrasive-water mixture jet [1]

Water jetting technology, especially AWJ machining, is a very flexible process, which can be used for any known material. Additionally, there is almost no heat affected zone on the machined part. He found that the material removal process was a cyclic penetration process that consists of two cutting regimes which he termed as cutting wear zone and deformation wear zone.

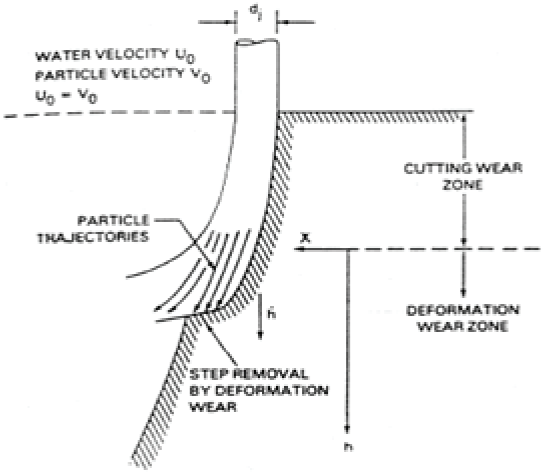


Fig. 4 A schematic of mechanism of material removal in water jet machining [1]

It is evident that the cause of striation was the change to the mode of material destruction. The author divided the total depth of cut into two distinct zones, as shown in Fig. 4. In the upper zone, which was called "cutting wear zone"; the material was removed by the impacting of abrasive particles at shallow angles. In the lower zone which was called "deformation wear zone", the material removal process was unsteady and sequential steps were formed, leading to large particle impact angles and the formation of striations or waviness on the wall of the cut surface. The material removal rate is mainly determined by the kinetic energy of the abrasive particles. When the kinetic energy of the local particles is higher than the required energy to destruct the work material, the material removal occurs (i.e. the jet penetration rate > 0). However, the distribution of the particle kinetic energy in a jet is not uniform and has a wavy profile in the jet cross-section, which results in non-uniform material removal, particularly at the lower portion of the cutting front (lower cutting zone). This non-uniformity contributes to the wavy striation to be formed on the cut surface. In the upper zone of the cut surface, most particles have a sufficient level of kinetic energy to cut or destruct the work material, so that the cut surface is almost free of striation. If the workpiece thickness is less than the depth of this zone, a smooth cut surface can be obtained all over the cutting front. As the particles penetrate into the work material, the number of particles that have the kinetic energy above the threshold value for cutting the material decreases. This results in more particles whose kinetic energy falls below the threshold value for destructing the work material. The present authors have illustrated this phenomenon in a more comprehensive model as in Fig. 4. The strong forefront particle cluster continues to cut through the surface whilst the weak trailing particle cluster is unable to do so by its own energy but follows the traces of the other particles with high energy. This leaves wavy and rough trace marks on the surface. These wavy marks are generally called striations, as depicted in Fig. 4. In addition, the striation drag angle depends on the ratio of the jet traverse speed in the horizontal direction to the jet vertical penetration rate. As the cutting depth increases, the jet cutting power becomes comparatively small so that the particle penetration rate decreases. With a constant jet traverse speed, this ratio increases, resulting in an increase in the striation drag angle as the cutting depth increases.

B.Processing Conditions

In water jet machining and abrasive water jet machining processes, selection of processing parameters and the process outputs are important. The regular process outputs involve: material removal rate (MRR), nozzle wear rate (NWR) and surface roughness (Ra). However, selection of the process outputs should be supported by practical experimentations and demonstrations. Experimental investigations showed that during abrasive jet machining with different abrasives, the width of cut at the top of the slot was always greater than that at the bottom of the slots. The phenomena could be, as the abrasive particles move down the jet, they lose their kinetic energy and the relative strength zone of the jet is narrowed down. As a result, the width of cut at the bottom of the slot is smaller than that at the top. In the present study, pressure (P), standoff distance between jet and the workpiece material (S_d) and abrasive flow rate (A_f) were chosen as the processing parameters. The parameters, units and their levels are shown in Table 1.

TABLE I PROCESSING PARAMETERS AND THEIR LEVELS FOR ABRASIVE WATER JET MACHINING PROCESS

Processing parameter	Levels of parameters		
	Level 1	Level 2	Level 3
P (MPa)	100	200	300
S_d (mm)	2.0	4.0	6.0
A_f (g/s)	3.0	5.0	7.0

The Taguchi L_{27} orthogonal array was chosen for the experimentation. The process output chosen for the investigation is surface roughness, which is an indicative of the quality of water jet machined surfaces. The experimental conditions, their levels for each experiment and the process outputs are shown in Table II.

The entire experiments were replicated once and the results were used in the data analysis. This is to evaluate the effect of processing conditions on the process output (quality of the surfaces machined using abrasive water jet machining process).

Table II Processing Conditions For Abrasive Water Jet Machining Process, And The Measured Process Output, Ra in μm

Sl. No	Pressure, P (MPa)	Stand-off distance, S_d (mm)	Abrasive flow rate, A_f (g/s)	Surface roughness, Ra (μm)
1	100	2	3	5.3
2	100	2	3	4.8
3	100	2	3	4.5
4	100	4	5	5.1
5	100	4	5	3.7
6	100	4	5	4.2
7	100	6	7	4.7
8	100	6	7	3.7
9	100	6	7	5.2
10	200	2	5	4.3
11	200	2	5	3.9
12	200	2	5	5.4
13	200	4	7	4.2
14	200	4	7	4.6
15	200	4	7	3.9
16	200	6	3	4.5
17	200	6	3	3.6
18	200	6	3	5.2
19	300	2	7	4.7
20	300	2	7	4.4
21	300	2	7	3.8
22	300	4	3	5.1
23	300	4	3	4.9
24	300	4	3	4.4
25	300	6	5	4.7
26	300	6	5	3.8
27	300	6	5	4.2

II. Results and Discussion

The measured values of surface roughness are presented in Table II. The experiments were replicated once; therefore 54 experiments were performed in total. After the experimentation and measurement of process output, the analysis of the data obtained was performed. This parametric analysis involved evaluation of the surface quality as a function of the processing conditions. The results of the parametric analysis is presented, please refer Table III.

The analysis show that the flow rate of the abrasive is most influential on the quality of surfaces machined using abrasive water jet machining. This is followed by pressure and stand-off distance. The AOM results are shown in Figs. 5, 6 and 7. The AOM plots presented in Fig. 5 show that the surface roughness decreases with an increase in the flow rate of the abrasive particles. As the flow rate of the particles increases from 3 to 5 grams per second, the decrease is more drastic. Therefore, it is evident that an increase in abrasive flow upto certain level causes a smoothening effect on the surface irregularities of the abrasive water jet machined surfaces.

Table III Results of Analysis of Variance For Abrasive Water Jet Machining Process

	DOF	Seq SS	Adj SS	Adj MS	F	P
P	2	0.3081	0.3081	0.1541	0.54	0.584
S_d	2	0.2593	0.2593	0.1296	0.46	0.636
A_f	2	1.3793	1.3793	0.6896	2.43	0.099
Error	47	13.317	13.317	0.2833		
Total	53	15.263				

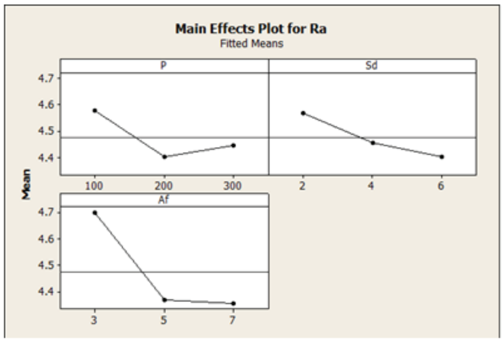


Fig. 5 AOM plots for surface roughness in the abrasive water jet machining process

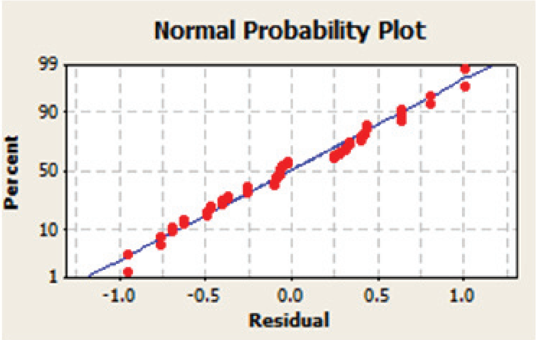


Fig. 6 Normal probability plot for the abrasive water jet machining data

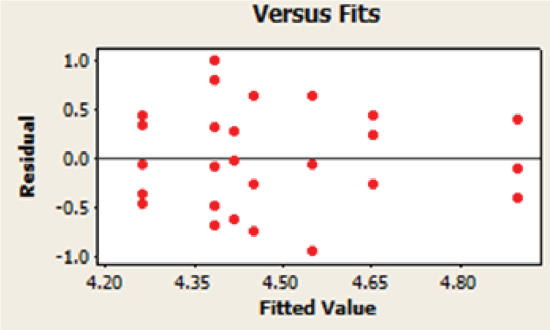
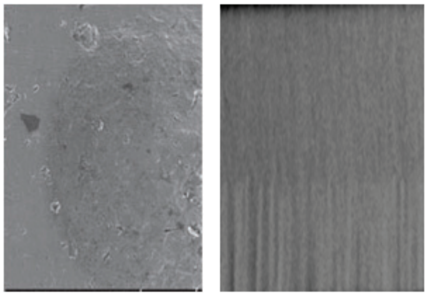


Fig. 7 Residual plots for the process output surface roughness, Ra (µm)

Typical abrasive water jet-machined surfaces obtained at different processing conditions are shown in Fig. 8 *a-b*. It is evident that there are several features such as micro-cracks, scratch-marks and depositions on the surface.



a. *b.*

Fig. 8 *a-b* The micrographs of abrasive water jet machined surfaces at different processing conditions

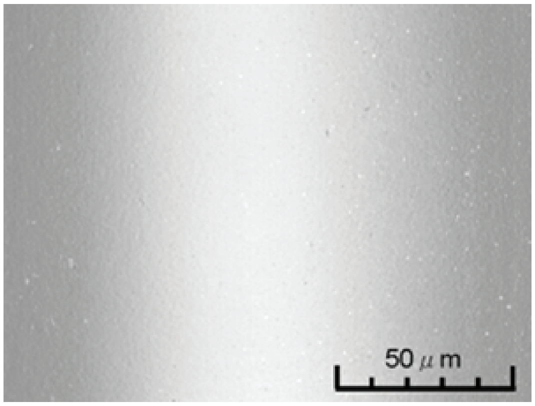


Fig. 9 The SEM micrograph indicating the quality of surface machined using abrasive water jet machining [3]

The optimum quality of surface obtained for a polishing application is presented in Fig. 9.

V. CONCLUSIONS

This paper has presented the experimental investigation and analysis of water jet machining process. The background of the process and mechanism of material removal were assessed in detail. The results of this experimentation and analysis of the results have indicated that abrasive flow rate was the most significant parameter in influencing the quality of surfaces machined using abrasive water-jet machining. The AOM analysis has indicated a drastic decrease in the surface roughness with an increase in abrasive flow rate from 3 to 5 g/s. The micrographic analysis of surfaces machined using the process indicated the presence of micro-cracks, depositions and similar features. This investigation has shown a possibility of applying the abrasive water-jet machining process for polishing applications mainly by controlling the size as well as the velocity of abrasive particles.

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