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Effects of Process Parameters on Surface Roughness in Abrasive Water jet Cutting of Borosilicate Glass

[1] Dr. M. Chithirai Pon Selvan [2] Jerrin Varghese
[1]Associate Professor – Mechanical Engineering, Amity University, Dubai, UAE
[1]Lecturer – Aerospace Engineering, Amity University, Dubai, UAE

Abstract: **Abrasive water jet cutting (AWJC) is a novel cutting process capable of cutting wide range of hard-to-cut materials. This paper presents an investigation on surface roughness which is an important cutting performance measure in abrasive water jet cutting of borosilicate glass. Taguchi's design of experiments was carried out in order to collect surface roughness values. Experiments were conducted in varying the traverse speed, abrasive flow rate, standoff distance and water pressure for cutting borosilicate glass using abrasive water jet cutting process. The effects of these parameters on surface roughness have been studied based on the experimental results.**

***Index Terms*— abrasive water jet, garnet, borosilicate glass, water pressure, mass flow rate, traverse speed, standoff distance.**

I. INTRODUCTION

In recent years many new materials like titanium alloys, hast alloys, nimonic alloys, composites etc. have been developed. These materials are used in space crafts, nuclear reactors, special cutting tools, turbine injectors etc. These new materials cannot be accurately machined by the conventional machining processes. Abrasive water jet cutting (AWJC) is superior to many other unconventional machining processes in processing variety of materials, particularly difficult-to-cut materials and has found extensive applications in industry. In this method, water serves primarily as an accelerating medium, whereby material removal is achieved by the abrasive particles. A stream of small abrasive particles is introduced in the water jet in such a manner that water jet 's momentum is partly transferred to the abrasive particles. As water accelerates large quantities of abrasive particles to a high velocity, a high coherent jet is achieved. This jet is then directed towards the working area to perform cutting (Hashish, 1989).

The technology's main advantage is the absence of a heat-affected zone in the materials processed that makes it particularly suitable for processing composites, ceramics and other materials where limiting heat flux into the work piece is critical. It gives less sensitive to material properties, does not cause chatter, imposes minimum stress on the work piece and high machining versatility and flexibility (Momber and Kovacevic, 1997). It is also a cost effective and environmentally friendly technique that can be adopted for processing a number of engineering materials particularly difficult-to-cut materials such as ceramics, composites, marbles, titanium (Siores et al., 1996 and Wang, 2003). Because of these capabilities, it makes an important contribution to machining materials with higher performance than traditional and other non-traditional machining processes. However, AWJC has some limitations and drawbacks. It may generate loud noise and a messy working environment. It may also create tapered edges on the kerf, especially when cutting at high traverse rates (Azmir and Ahsan, 2008 and Ma and Deam 2006).

Abrasive water jet cutting process incurs relatively higher initial investment, maintenance and operating costs. Therefore optimum choice of the process parameters is essential for the economic, efficient and effective utilization of this process. There are numerous variable process parameters which influence the quality of the abrasive water jet cutting (Kovacevic, 1992). These parameters include water pressure, water jet diameter, nozzle traverse speed, number of passes, standoff distance, impact angle, nozzle diameter, nozzle length, abrasive mass flow rate, abrasive particle diameter, abrasive particle shape and abrasive particle hardness. Among these variable parameters water pressure, abrasive flow rate, jet traverse rate and standoff distance are important which are precisely controllable (John Rozario Jegaraj and Ramesh Babu, 2007 and Shanmugam et al., 2008).

The main process quality measures include attainable depth of cut, top kerf width, bottom kerf width, kerf taper, surface roughness, surface waviness and material removal rate. A number of techniques for improving kerf quality and depth of cut have been proposed (Chithirai Pon Selvan et al., 2016, Shanmugam and Masood, 2009, Lemma et al., 2002 and Wang et al., 2003).

In this paper surface roughness is considered as the performance measure as in many industrial application it is the main constraint on the process applicability. More work is required to fully understand the influence of the important process parameters on surface roughness of Borosilicate glass. Therefore experimental and theoretical studies have been undertaken in this project to investigate the effects of water pressure, nozzle traverse speed, abrasive mass flow rates, standoff distance on surface roughness of borosilicate glass.

II. EXPERIMENTAL WORK

a. Material

Borosilicate glass is a type of glass with silica and boron trioxide as the main glass-forming constituents. Borosilicate glasses are known for having very low coefficients of thermal expansion (~3 × 10−6 /°C at 20° C), making them resistant to thermal shock, more so than any other common glass. Such glass is less subject to thermal stress and is commonly used for the construction of reagent bottles. Borosilicate glass is created by adding boric oxide to the traditional glassmaker's frit of silica sand, soda, and ground lime. The common type of borosilicate glass used for laboratory glassware has a very low thermal expansion coefficient about one-third that of ordinary soda-lime glass. This reduces material stresses caused by temperature gradients which makes borosilicate a more suitable type of glass for certain applications. While more resistant to thermal shock than other types of glass, borosilicate glass can still crack or shatter when subjected to rapid or uneven temperature variations. When broken, borosilicate glass tends to crack into large pieces rather than shattering. Borosilicate glass is less dense (at about 2.23g/cm3) than typical soda-lime glass due to the low atomic weight of boron. The temperature differential borosilicate glass can withstand before fracturing is about 165.56 °C. This compares well with soda lime glass, which can withstand only a 37.22 °C change in temperature and is why "Pyrex" kitchenware (soda lime glass) will shatter if a vessel containing boiling water is placed on ice, but Pyrex laboratory equipment (borosilicate glass) will not.

b. Equipment

The equipment used for machining the samples was Water Jet Sweden cutter - CLASSICA which was equipped with KMT ultrahigh pressure pump with the designed pressure of 4000 bar. The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve and a work piece table with dimensions of 3000 mm x 1500 mm. Sapphire orifice was used to transform the high-pressure water into a collimated jet, with a carbide nozzle to form an abrasive water jet . Throughout the experiments, the nozzle was frequently checked and replaced with a new one whenever the nozzle was worn out significantly. The specifications of abrasive water jet cutting equipment used for the experiments are shown in table 1 and the equipment used for this study is shown in figure 1.

Table 1 Specifications of abrasive water jet cutter

Machine Model	Classica-50 HP (KMT)
Energy consumption (kWh)	37
Abrasive consumption (g/min)	100-900
Nozzle diameter (mm)	1.05
Nozzle length (mm)	76.5
Water consumption (lt/min)	3.6

Figure 1 Abrasive water jet cutting equipment

c. Design of Experiments (DOE)

Design of experiments (DOE) is a powerful tool that can be used in a variety of experimental situations. DOE techniques enable designers to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. To achieve a thorough cut it was required that the combinations of the process variables give the jet enough energy to penetrate through the specimens. In the present study four process parameters were selected as control factors. The parameters and levels were selected based on the literature review of some studies that had been documented on AWJC on metallic coated sheet steels (Wang and Wong, 1999) and fiber-reinforced plastics (Hocheng et al., 1997). The process parameters and their ranges are as follows: water pressure 200 MPa to 350 MPa, nozzle traverse speed from 1.6 mm/s to 4.2 mm/s, standoff distance 1.8 mm to 5 mm and mass flow rate of abrasive particles from 2.5 g/s to 5.5 g/s. Table 2 shows the levels of parameters used in experiment.

Table 2 Levels of parameters used in experiment

Parameters	Unit	Level 1	Level 2	Level 3
Water pressure (p)	MPa	200	275	350
Traverse speed (u)	mm/s	1.6	2.9	4.2
Mass flow rate ($m_{a)}$)	g/s	2.5	4	5.5
Standoff distance (s)	mm	1.8	3.4	5

Taguchi's experimental design was used to construct the design of experiments (DOE). Four process parameters, each varied at three levels, an L_9 (3^4) orthogonal arrays table with 9 rows was selected for the experimentation. This experimental design yielded 9 test runs. In order to produce sufficient “as measured” data for statistical analysis and graphic representation, additional tests were added to the experimental design.

d. Data Collection

For each experiment, the machining parameters were set to the pre-defined levels according to the orthogonal array. All machining procedures were done using a single pass cutting. The abrasives were delivered using compressed air from a hopper to the mixing chamber and were regulated using a metering disc. The abrasive flow rates were calibrated by measuring the time spent for a certain weight of abrasives to be completely consumed in the hopper. The supply pressure was manually controlled using a pressure gauge. The standoff distance is controlled through the controller in the operator control stand. The traverse speed and supply of abrasives were automatically controlled by the abrasive water jet system programmed by NC code.

The surface finish parameter employed to indicate the surface quality in this experiment was the arithmetic mean roughness (Ra). Workpiece surface roughness Ra was measured by a surface roughness equipment model “SURFPAK SV-514”. Surface roughness was measured at the centre of the cut for each specimen. Each measurement of Ra was taken three times and their arithmetic mean was calculated as to minimize the error.

III. RESULTS AND DISCUSSIONS

Surface roughness is one of the most important criteria, which help us determine how rough a work piece material is machined. In all the investigations it was found that the machined surface is smoother near the jet entrance and gradually becomes rougher towards the jet exit. This is due to the fact that as the particles moves down they loose their kinetic energy and their cutting ability deteriorates. By analyzing the experimental data, it has been found that the optimum selection of the four basic parameters, i.e., water pressure, abrasive mass flow rate, nozzle traverse speed and nozzle standoff distance are very important on controlling the surface roughness. The effect of each of these parameters is studied while keeping the other parameters considered in this study as constant. The following discussion uses the experimental data at the centre of the cut for each specimen and the surface roughness is assessed based on the centre-line average Ra.

The effects of process parameters on surface roughness during cutting of Granite are shown in figures 2, 3, 4 and 5. Figure 2 shows the effect of water pressure on surface roughness. In this experimental study, mass flow rate, traverse speed and standoff distance were kept at 5.5 g/s, 1.6 mm/s and 5 mm respectively. The surface roughness gradually decreases when the water pressure from increases 200 MPa to 350 MPa. Figure 3 shows the trend in change in surface roughness with increase in mass flow rate. During the cutting process the water pressure was 350 MPa, traverse speed was 1.6 mm/s and standoff distance was 5 mm. As the mass flow rate is increased from 2.5 g/s to 5.5 g/s, the surface roughness is decreased. Figure 4 shows the relationship between traverse speed and surface roughness. The other three process parameters namely, mass flow rate, water pressure and standoff distance were kept constant at 5.5 g/s, 350 MPa and 5 mm respectively. The general trend of the curve shows that increase in traverse speed from 1.6 mm/s to 4.2 mm/s results in increase in surface roughness. Figure 5 shows the relationship between standoff distance ranging from 1.8 mm to 5 mm and surface roughness. During the cutting process mass flow rate, water pressure and traverse speed were 1.6 g/s, 350 MPa and 5.5 mm/s respectively. An increase in surface roughness is seen when the standoff distance is increased.

A. *Effect of Water Pressure on Surface Roughness*

The influence of water pressure on the surface roughness is shown in fig. 2. Jet pressure plays an important role in surface finish. As the jet pressure increases, surface becomes smoother. With increase in jet pressure, brittle abrasives break down into smaller ones. As a result of reduction of size of the abrasives the surface becomes smoother. Again, due to increase in jet pressure, the kinetic energy of the particles increases which results in smoother machined surface.

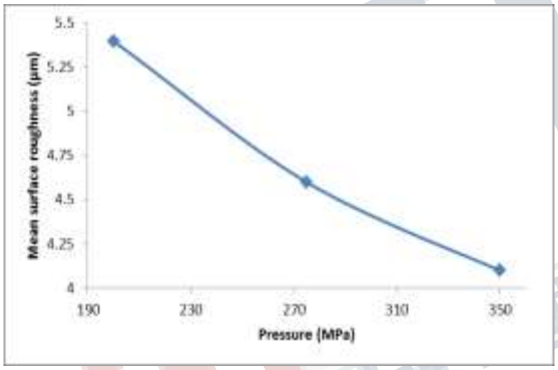

Fig. 2. Water pressure versus surface roughness

B. *Effect of Mass Flow Rate on Surface Roughness*

It needs a large number of impacts per unit area under a certain pressure to overcome the bonding strength of any material. With the increase in abrasive flow rate, surface roughness decreases. This is because of more number of impacts and cutting edges available per unit area with a higher abrasive flow rate. Abrasive flow rate determines the number of impacting abrasive particles as well as total kinetic energy available. Therefore, higher abrasive flow rate, higher should be the cutting ability of the jet. But for higher abrasive flow rate, abrasives collide among themselves and loose their kinetic energy. It is evident that the surface is smoother near the jet entrance and gradually the surface roughness increases towards the jet exit. The effect of abrasive mass flow rate on surface roughness is shown in fig. 3.

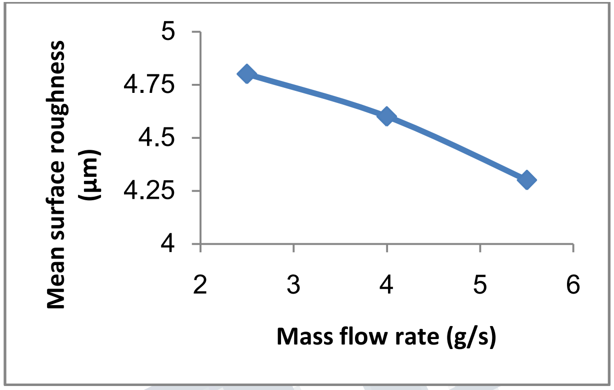

Fig. 3. Abrasive mass flow rate versus surface roughness

C. *Effect of Traverse Speed on Surface Roughness*

Traverse speed didn't show a prominent influence on surface roughness. For decreasing of the machining costs every user try to choose the feed rate of the cutting head as high as possible, but increasing the traverse speed always causes increasing of inaccuracy and surface roughness. But with increase in work feed rate the surface roughness increased. This is due to the fact that as the work moves faster, less number of particles are available that pass through a unit area. Therefore, less number of impacts and cutting edges are available per unit area, which results a rougher surface. The relationship between the traverse speed and the surface roughness is shown in fig. 4.

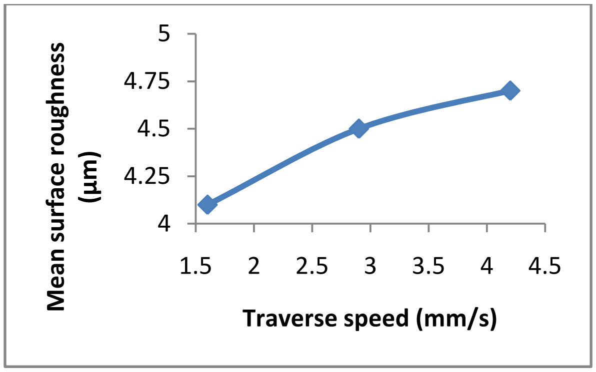

Fig. 4. Traverse speed versus surface roughness

D. *Effect of Standoff Distance on Surface Roughness*

Surface roughness increase with increase in standoff distance as shown in fig. 5. Generally, higher standoff distance allows the jet to expand before impingement which may increase vulnerability to external drag from the surrounding environment. Therefore, increase in the standoff distance results an increased jet diameter as cutting is initiated and in turn, reduces the kinetic energy of the jet at impingement. So surface roughness increase with increase in standoff distance. It is desirable to have a lower standoff distance which may produce a smoother surface due to increased kinetic energy. The machined surface is smoother near the top of the surface and becomes rougher at greater depths from the top surface.

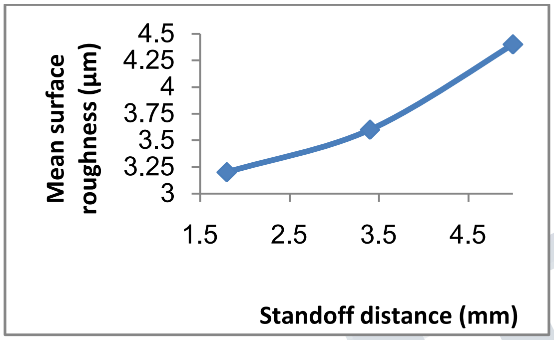

Fig. 5. Standoff distance versus surface roughness

IV CONCLUSIONS

Experimental investigations have been carried for the surface roughness in abrasive water jet cutting of borosilicate glass. The effects of different operational parameters such as: pressure, abrasive mass flow rate, traverse speed and nozzle standoff distance on surface irregularities have been investigated.

As a result of this study, it is observed that these operational parameters have direct effect on surface roughness. It has been found that water pressure has the most effect on the surface roughness. An increase in water pressure is associated with a decrease in surface roughness. These findings indicate that the use of high water pressure is preferred to obtain good surface finish. Surface roughness constantly decreases as mass flow rate increases. It is recommended to use more mass flow rate to decrease surface roughness. Among the process parameters considered in this study water pressure and abrasive mass flow rate have the similar effect on surface roughness. As nozzle traverse speed increase, surface roughness increases. This means that low traverse speed should be used to have more surface smoothness but is at the cost of sacrificing productivity. This experimental study has resulted surface smoothness increase as standoff distance decreases. Therefore to achieve an overall cutting performance, low standoff distance should be selected. Finally it is recommended that a combination of high water pressure, more abrasive mass flow rate, low traverse speed and short standoff distance be used to produce more surface smoothness.

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