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Maximum Depth of Cut for Borosilicate Glass using Abrasive Waterjet Technique

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ABSTRACT

In recent years many new materials have been developed. These materials include titanium alloys, hast alloys, nimonic alloys, composites etc. 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 waterjet cutting is superior to many other non-traditional machining processes in processing variety of materials, particularly difficult-to-cut materials and has found extensive applications in industry. Abrasive waterjet 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. In this research work both experimental and theoretical studies have been undertaken to investigate the effects process parameters namely, water pressure, nozzle traverse speed, abrasive mass flow rates and standoff distance on depth of cut in abrasive waterjet cutting of borosilicate glass. It was experimentally demonstrated that the good cutting performance can be achieved by selecting the right combination of process parameters.

Key words: Abrasive waterjet, garnet, borosilicate glass, water pressure, mass flow rate, traverse speed, standoff distance

INTRODUCTION

Manufacturing industry is becoming ever more time conscious with regard to the global economy. The need for rapid prototyping and small production batches is increasing in modern industries. These trends have placed a premium on the use of new and advanced technologies for quickly processing raw materials into usable goods; with no time being required for tooling. Material cutting by abrasive waterjets was first commercialized in the late 1980's as a pioneering breakthrough in the area of unconventional processing technologies. Since that time various aspects of this cutting technique have been investigated by many specialists all over the world. In Abrasive Waterjet Cutting (AWJC) 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 waterjet in such a manner that waterjet'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 [1].

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 workpiece is critical. It gives less sensitive to material properties, does not cause chatter, and imposes minimum stress on the work piece and high machining versatility and flexibility [2]. 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 [3-4]. 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 [5-6].

As in the case of every machining process, the quality of AWJC process is significantly affected by the process tuning parameters [7]. There are numerous associated parameters in this technique. They are water pressure, waterjet 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 parameters water pressure, abrasive flow rate, jet traverse rate, standoff distance and diameter of focusing nozzle are of great importance but precisely controllable [8-9]. The right choice of process parameters is very important for good cutting performance. 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 surface finish have been proposed [10-12]. More work is required to fully understand the effects of process input parameters on depth of cut in abrasive waterjet cutting technology. Researchers did a number of experiments on cutting of different grades of steel, copper, aluminium, 87% alumina ceramics, different types of stone etc. by AWJC [13].

In this paper depth of cut 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 depth of cut 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 depth of cut of borosilicate glass.

EXPERIMENTAL WORK

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.

Equipment

The equipment used for machining the samples was Water Jet Sweden cutter 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 dimension 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 waterjet. Throughout the experiments, the nozzle was frequently checked and replaced with a new one whenever the nozzle was worn out significantly. The abrasives were delivered using compressed air from a hopper to the mixing chamber and were regulated using a metering disc. The debris of material and the slurry were collected into a catcher tank. The specifications of abrasive waterjet cutting equipment used for the experiments are shown in table- 1.

Table -1 Specifications of abrasive waterjet 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

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	mm	1.8	3.4	5

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 [14] and fiber-reinforced plastics [15]. 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. 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 as shown in table 3 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.

Table -3 Experimental design using L_9 orthogonal arrays

Experiment No.	Level of Water pressure	Level of Traverse speed	Level of Mass flow rate	Level of Standoff distance
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

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 waterjet system programmed by NC code. The depth of cut for each test was measured by using a "SigmaScope 500" profile projector at a magnification of 10 times. With this magnification together with a large shadow screen on the projector and precision digital readouts, the measurement accuracy was expected to be more than adequate for the purpose of this study. For each cut, at least three measures were made and the average was taken as the final reading.

RESULTS AND DISCUSSION

Based on the experimental results, the effects of the four basic parameters, i.e., water pressure, abrasive mass flow rate, nozzle traverse speed and nozzle standoff distance on the depth of cut have been reported as below. The effect of each of these parameters is studied while keeping the other parameters considered in this study as constant. The effects of process parameters on depth of cut during cutting of granite are shown in Figs 1 to 4. Fig. 1 shows the effect of water pressure on depth of cut. 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 depth of cut gradually increases when the water pressure increases from 200 MPa to 350 MPa. Fig. 2 shows the trend in change in depth of cut 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 depth of cut is also increased. Fig. 3 shows the relationship between traverse speed and depth of cut. 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 decrease in depth of cut. Fig. 4 shows the relationship between standoff distance ranging from 1.8 mm to 5 mm and the depth of cut. During the cutting process mass flow rate, water pressure and traverse speed were 5.5 g/s, 350 MPa and 1.6 mm/s respectively. A slight decrease in depth cut is seen when the standoff distance is increased.

Effect of Water Pressure on Depth of Cut

Results indicate that, within the operating range selected, increase of water pressure results in increase of depth of cut when mass flow rate, traverse speed and standoff distance were kept constant. Abrasive particles gain higher velocity, and hence higher energy, under an increased water pressure and as a result, remove more materials. Increasing the water pressure is the most effective method of increasing the cutting ability. The main reason for this is that the transfer rate of momentum and the velocity from the jet to the particles at the nozzle exit is increased in accordance with the water pressure, thus resulting in increased impact energy and accordingly the depth of cut.

Effect of Mass Flow Rate on Depth of Cut

Increase in abrasive mass flow rate also increases the depth of cut. The impact between the abrasive particle and the material determines the ability of the abrasive waterjet to cut the material. Since cutting is a cumulative process, the speed of the abrasive particle and the frequency of particle impacts are both important. The speed of the particle determines the impulsive loading on the material and the potential energy transfer from the particle to the material. The frequency of the impact determines the rate of energy transfer and hence, the rate of cut depth growth. The mass flow rate of the abrasive particles partially determines not only the frequency of the impacting particles but also the speed at which they hit. In addition, with the greater mass flow rates, the kinetic energy of the water must be spread over more particles. Therefore, the depth of cut goes down with the increased mass flow rate.

Effect of Traverse Speed on Depth of Cut

Traverse speed is the advance rate of nozzle on horizontal plane per unit time during cutting operation. Results indicate that increase of traverse speed decreases the depth of cut within the operating range selected, by keeping the other parameters considered in this study as constant. The longer the abrasive waterjet stays at a particular location, the deeper the cut will be because the stream of abrasive particles has more time to erode the material. This effect is due to two reasons. First the longer the dwell time the greater the number of impacting abrasive particles hit the material and the greater the micro damage, which starts the erosion process. Secondly, the water from the jet does have a tendency to get into the micro cracks and because of the resulting hydrodynamic pressure, the crack growth results. When the micro cracks grow and connect, the included material will break loose from the parent material and the depth of cut increases. For this reason, it seems reasonable to expect an inverse relationship between the traverse speed and the depth of cut.

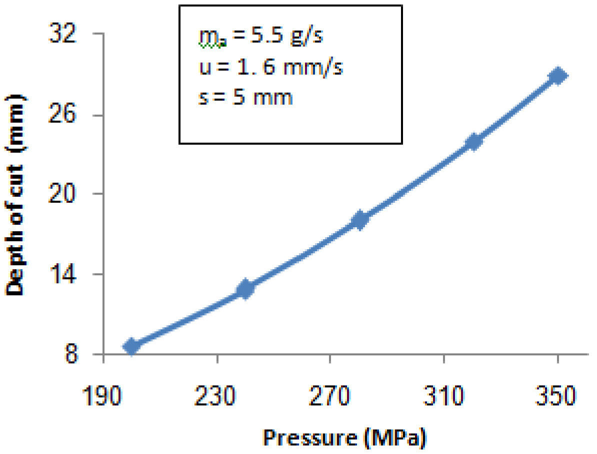

Fig. 1 Water pressure versus depth of cut

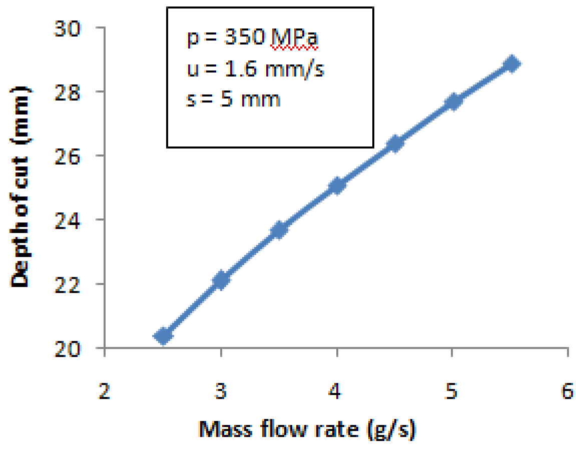

Fig. 2 Abrasive mass flow rate versus depth of cut

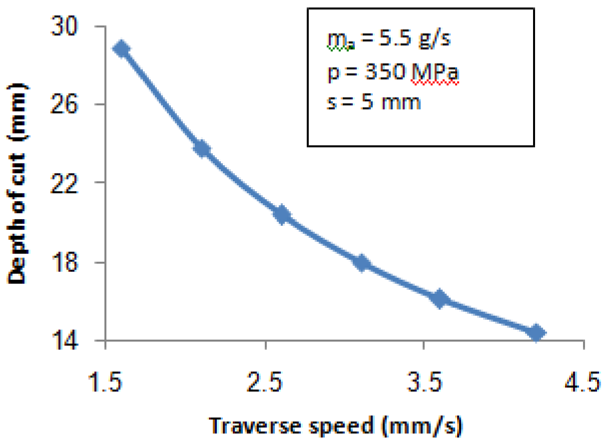

Fig. 3 Traverse speed versus depth of cut

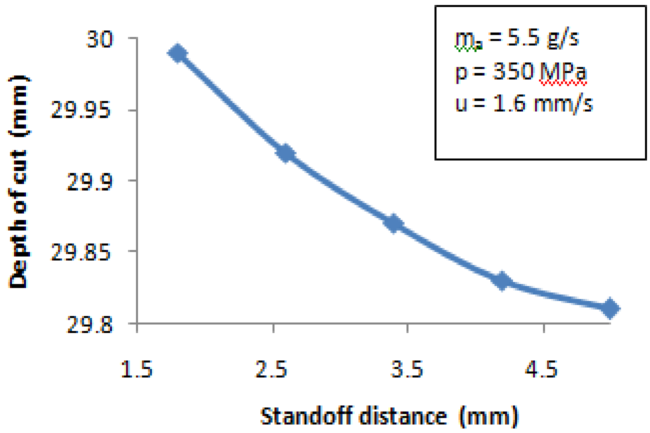

Fig. 4 Standoff distance versus depth of cut

Effect of Standoff Distance on Depth of Cut

Standoff distance is the distance between the nozzle and the work piece during cutting operation. The study showed that width of cut increases as the stand-off distance of the nozzle from the work is increased which is due to divergence shape of the abrasive water-jet. If we keep the other operational parameters constant, when standoff distance increases, depth of cut decreases. However standoff distance on depth of cut is not much influential when compared to the other parameters considered in this study. The decrease of the depth of cut with an increase in standoff distance, although in a small rate, may be attributed to the fact that the particle velocity is reduced as the jet flows away from the nozzle when the standoff distance is increased. This results in less material to be removed and a reduced depth of cut.

CONCLUSION

Experimental investigations have been carried for the depth of cut and surface roughness in abrasive waterjet cutting of borosilicate glass. The effects of different operational parameters such as: pressure, abrasive mass flow rate, traverse speed and nozzle standoff distance on depth of cut have been investigated. As a result of this study, it is observed that these operational parameters have direct effect on depth of cut.

- Water pressure has the maximum effect on the depth of cut. An increase in water pressure is associated with an increase in depth of cut. These findings indicate that the use of high water pressure is preferred to obtain overall good cutting performance.
- Depth of cut constantly increases as mass flow rate increases. It is recommended to use more mass flow rate to increase depth of cut.
- Among the process parameters considered in this study water pressure and abrasive mass flow rate have similar effect on the major cutting performance measures.
- As nozzle traverse speed increases, the depth of cut decreases. This means that low traverse speed should be used to have more depth of cut, but this is at the cost of sacrificing productivity
- This experimental study has resulted that standoff distance has minimal effect on depth of cut. It is desirable to have a lower standoff distance which produces more depth of cut due to increased kinetic energy.

This experimental study reveals that selection of correct combination of process parameters is critical to achieve overall good cutting performance. This research also experimentally demonstrated that if the cutting parameters are not selected properly, AWJC can reduce the depth of cut. 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 depth of cut.

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