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TURNING OF GLASS WITH ABRASIVE WATERJET

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ABSTRACT

This article reports research results on abrasive waterjet (AWJ) turning of glass. Glass rods, 25 mm in diameter, were turned by using AWJ to investigate the effects of several process parameters on the surface quality of the machined glass surfaces. The parameters studied are rotational speed, stand-off distance, water pressure, nozzle traverse speed, and abrasive flow rate. The results were also compared with those obtained from conventional machining of glass. The results showed that higher traverse rates were associated with an increase in material removal rate and thus an increase in surface roughness and waviness values. The sensitivity of surface quality to rotational speed was more than that to the traverse speed. Good surface finish was achieved at lower traverse speeds and higher turning speeds. Higher stand-off produced rougher surface finish. The best finish was generated when the nozzle consumed 300 g min^{-1} of abrasives. Higher pressures did not produce smoother surface finish.

Key Words: Abrasive waterjet; Difficult-to-machine materials; Abrasive waterjet turning; Glass; Process parameters; Surface finish; Rotational speed; Stand-off distance; Water pressure; Nozzle traverse speed; Abrasive flow rate; Grinding; Lapping; Fractured surface; Material removal rate

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INTRODUCTION

The waterjet cutting, also called hydrodynamic machining, technology was developed in 1968 by Dr. Norman Franze, followed by the first commercial system in 1971. A breakthrough was made by adding abrasive particles to the high-pressure stream of water in the early 1980s, immediately followed by the introduction of the first commercial abrasive waterjet (AWJ) system in 1983. AWJ machining was also called hydrobrasive machining[1,2].

When water is pressurized to an ultrahigh pressure up to about 400 MPa or 60,000 psi, and discharged from a small orifice, the waterjet can cause damage to materials by shearing, cracking, erosion, cavitation, delamination, and plastic deformation. The cutting power is increased by adding abrasive particles into the high velocity water stream. Water serves as an accelerating medium and the abrasive particles play the role of a material removal. Mixing and acceleration of abrasive particles in the water stream can be achieved in several configurations[3].

An AWJ system typically consists of a nozzle assembly, a high-pressure pump, an abrasive delivery system, a motion system, a catcher system, and a control unit. The nozzle assembly provides an on/off control of the high-pressure water. The abrasive is fed by vacuum suction into the mixing chamber. The abrasive particles wear the WC cutting nozzle. The nozzle life is typically 1–4 hr when using garnet as the abrasive, or just 5 min when using Al_2O_3 as the abrasive. The AWJ nozzle life is also influenced by various AWJ cutting parameters[4]. A new nozzle made of a ceramic material called "boride" has been developed and the wear life of the new nozzles is from 10 to 100 times that of the WC nozzles[5].

An AWJ cutting process is governed by more than 16 parameters. These parameters include water pressure, waterjet orifice diameter, abrasive flow rate, abrasive type and size, mixing tube diameter and length, nozzle standoff distance, cutting jet angle, number of passes, traverse speed, the erosion resistance of the material to be cut, the method of abrasive delivery, pressure of abrasive slurry, the condition of abrasives, and the geometry of the nozzle assembly[3,6]. The quality of the surfaces cut by the AWJ varies significantly with the choice of cutting parameters. The variation of the roughness heights is significantly affected by the changes in the process characteristics and cannot be predicted by mathematical models. However, the surface quality can be estimated by measuring the workpiece normal force generated by the AWJ[7].

The velocity of a waterjet is proportional to the square root of water pressure. Increasing the pressure increases the abrasive particle velocity. This is associated with both favorable and unfavorable effects[8,9]. Cutting jet angle is the angle between the jet and the top surface of the workpiece. Typically, it is set to be 90°. A study reported that an angle slightly less than 90° in the opposite direction of the traverse direction was ideal to compensate the curvature change of the cutting front and the kerf width variation[10]. For ductile materials, the erosion resistance is closely related to the hardness. For brittle materials, more material parameters such as fracture toughness, grain size, flaw distribution parameter, etc. are involved[11].

AWJ technology offers the following advantages as compared to many of the other machining technologies: absence of heat-affected zone, essentially cold cut, no potential fire hazard, high machining versatility, omni-directional machining capability with no tool-wear problems, high cutting speed, high flexibility, the ability to cut almost any material including hard-to-cut materials such as steel, superalloys, composites, and advanced ceramics, low machining force, leaving surfaces free from thermal and mechanical distortion, the ability to drill holes with high-aspect ratios, etc.[1,4,6,12–15] The machining force is typically smaller than 10 N[16]. The small machining force allows machining of fragile or deformable materials and structures, such as glass and honeycomb structures. Therefore, AWJ turning is not sensitive to the length-to-diameter ratio of the workpiece. Long slender parts can be turned conveniently as the vibration and deformation problems caused by the large force in traditional turning or grinding process are eliminated. It also eliminates the need for strong and bulky fixtures[17].

AWJ machining has its limitations: energy dissipating characteristics and high initial capital cost. An AWJ continually loses its energy due to dissipation along its path. The cutting power of the jet decreases from the top surface to the bottom surface of the workpiece, leaving a tapered kerf and striation marks on the lower portion of the cut surface. Decreasing the traverse speed can minimize this energy-dissipating phenomenon. Other methods have also been proposed to compensate for the energy dissipation[9,10]. The costs of complete AWJ systems and hourly operating/maintenance costs depend on the requirements for power, controllers, complexity, and size of the systems[18].

AWJ is increasingly used to machine difficult-to-machine materials due to its numerous advantages[12–14]. Turning with AWJ is a relatively simple process. A waterjet nozzle is used, and the workpiece is rotated while the AWJ is traveled axially at the circumference of the workpiece to produce a turned surface. This process is less sensitive to the shape of the original part as compared with the conventional turning. For example, a highly irregular geometry can be cut in one pass with a large depth of cut to a surface of revolution.

This article provides results on AWJ turning of glass, as data on turning of brittle materials are still scarce. Glass rods of 25 mm in diameter were turned by using AWJ to investigate the effects of the process parameters on surface finish. Parameters such as rotational speed, stand-off distance, water pressure, nozzle transverse speed, and abrasive flow rate were studied. The results were also compared with those obtained from conventional machining of glass.

EXPERIMENTS

Borosillicate glass samples with 25 mm diameter were prepared for the experiments. Figure 1 shows the experimental set-up.

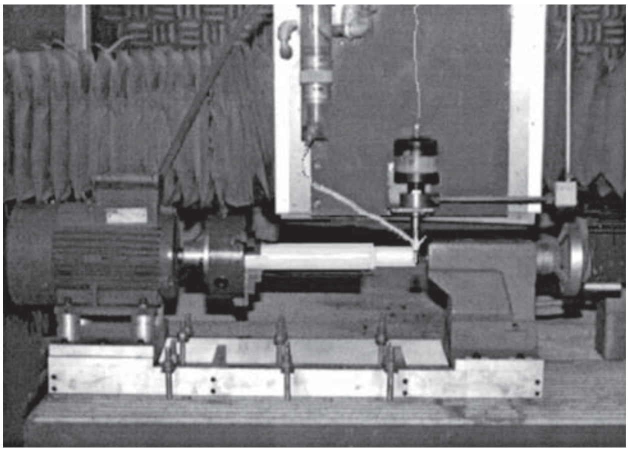

Figure 1. Experimental set-up for AWJ turning.

The experiments were carried out by using a custom-built lathe and a standard waterjet cutting system. The lathe was positioned in parallel to the system's *X*-axis. Rubber pads were placed underneath to suppress structural vibrations. The turning speed variation was made possible by using an inverter-controlled motor. The pump used was of an intensifier type, which was capable of pumping water pressures up to 400 MPa with a flow rate of 4 lpm. The abrasive feeder system consisted of a storage hopper, a flow control valve, and a feeding tube. The feeding mechanism could accurately control the abrasive flow up to 80 g sec^{-1}. Debris and spent abrasives were collected in a water-filled catcher tank.

Figure 2 shows a schematic diagram of the nozzle head used for the experiments. In this nozzle, pressurized water is expelled through a sapphire orifice to form a coherent high-velocity jet. The water jet and the stream of

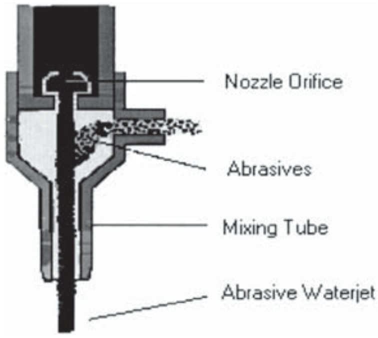

Figure 2. Abrasive waterjet cutting head.

abrasives are introduced into a tungsten carbide tube to form an AWJ at the exit of the nozzle.

During the experiments, the overall depth of cut was 2 mm after two passes for every run, i.e., the depth of cut per pass $d = 1$ mm. The glass workpiece was rotated on the lathe to produce a turned surface. The material was converted into fine debris during the turning process. The process variables for the experiments were rotational speed (S), jet transverse speed (F), jet stand-off (X), and abrasive flow rate (A_f). One parameter was varied for a set of experiments while the others were held constant. The nozzle orifice and mixing tube sizes were maintained at the most commonly used 13 thou ($\times$ 0.001 in.) and 40 thou, respectively. The abrasive selected for the experiments was 100 mesh-size Olivine.

After turning, the samples were inspected by using a surface analyzer to measure surface roughness R_a and surface waviness W_a values.

RESULTS AND DISCUSSION

The effects of the AWJ turning process parameters on the surface quality of the turned glass samples are shown in Figs. 3–7, in which the measured roughness R_a and waviness W_a values are plotted against one of the experimental variables.

In Fig. 3, the variable is water pressure and it increases from 100 to 300 MPa while other parameters are constant. Contrary to linear waterjet cutting, higher pressures did not produce smoother surface finish in this experiment. The best surface finish was obtained at 200 MPa water pressure. Above that, unsteadiness in traverse rate or abrasive flow rate probably became more critical and could have caused deterioration in surface quality.

Figures 4 and 5 show that the sensitivity of surface quality to rotational speed is more than that to the traverse speed. It was also observed from the figures that good surface finish was achieved at lower traverse speeds and higher turning speeds.

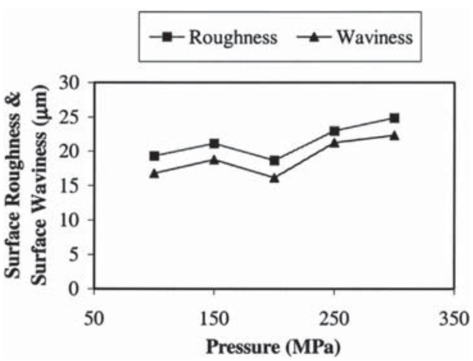

Figure 3. Surface finish vs. pressure ($F = 300\,\text{mm min}^{-1}$, $S = 900$ rpm, $X = 3$ mm, Af $= 200\,\text{g min}^{-1}$).

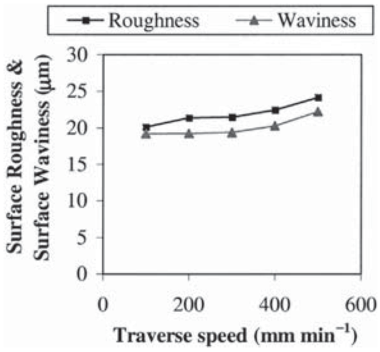

Figure 4. Surface finish vs. traverse speed ($P = 200\,\text{MPa}$, $S = 900\,\text{rpm}$, $X = 3\,\text{mm}$, $\text{Af} = 200\,\text{g min}^{-1}$).

The trend for stand-off variation can be seen in Fig. 6. Higher stand-off produced rougher surface finish. This was due to jet energy dispersion, which is a common scenario in linear waterjet cutting. The abrasive flow rate was varied from 162 to $300\,\text{g min}^{-1}$. The best finish ($R_a = 18.34\,\mu\text{m}$) shown in Fig. 7 was generated when the nozzle consumed $300\,\text{g min}^{-1}$ of abrasives. This was probably the optimal flow rate for 200 MPa water pressure.

Figures 8 and 9 show scanning electron microscope (SEM) pictures of the glass surfaces machined by AWJ turning, conventional grinding, lapping, and polishing. The glass samples machined by AWJ turning and conventional grinding are 100% fractured surfaces while lapped glass reveals some ductile streaks and polished glass shows a perfect mirror surface.

Figure 10 compares the surface roughness of glass surfaces machined by AWJ turning, conventional grinding, precision grinding, ultra-precision grinding,

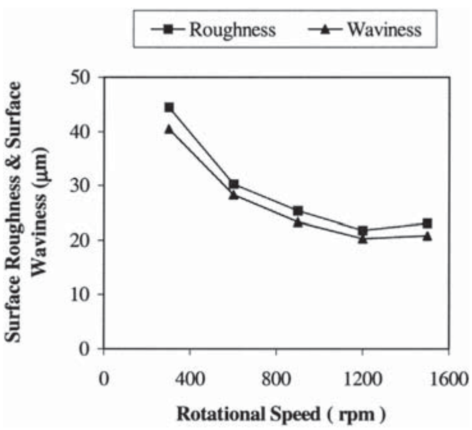

Figure 5. Surface finish vs. rotational speed ($P = 200\,\text{MPa}$, $F = 300\,\text{mm min}^{-1}$, $X = 3\,\text{mm}$, $\text{Af} = 200\,\text{g min}^{-1}$).

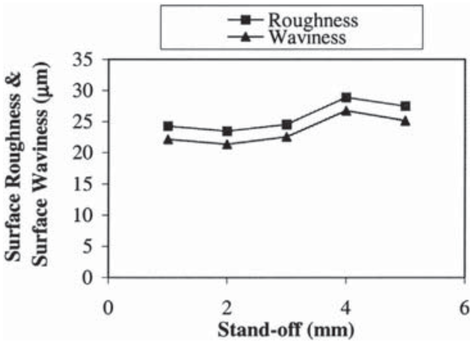

Figure 6. Surface finish vs. stand-off ($P = 200\,\text{MPa}$, $F = 300\,\text{mm min}^{-1}$, $S = 900\,\text{rpm}$, $\text{Af} = 200\,\text{g min}^{-1}$).

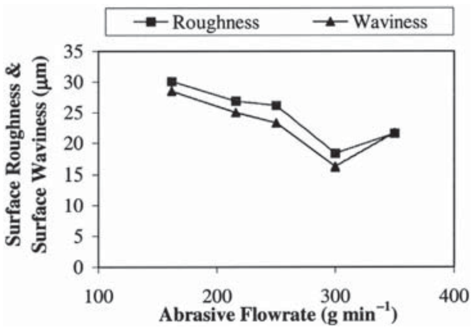

Figure 7. Surface finish vs. abrasive flow rate ($P = 200\,\text{MPa}$, $F = 300\,\text{mm min}^{-1}$, $S = 900\,\text{rpm}$, $X = 3\,\text{mm}$).

lapping, and polishing. The surface roughness R_a value of AWJ turned glass is much higher than those obtained from other machining processes.

However, the depths of cut of ultra-precision grinding and diamond turning are usually about 1 μm or even below 1 μm. The critical depth of cut to achieve ductile mode machining of glass was reported as 0.03 μm[19]. Ultrasonic vibration helped to increase the critical depth of cut to about seven times that of conventional diamond cutting. A very small roughness value $R_{max} = 0.03\,\mu\text{m}$ could be achieved by turning three times and applying ultrasonic vibration at normal depth of cut $d = 2\,\mu\text{m}$, feed rate $F = 7.5\,\mu\text{m min}^{-1}$, and rotational speed 1.5 rpm[19].

In contrast, one of the advantages of AWJ turning is that the material removal rate can be very high, as the depth cut per pass d, feed rate F, and rotational speed S can be set at large values. In the experiments reported in this article, $d = 1\,\text{mm}$, $F = 100–500\,\text{mm min}^{-1}$, and $S = 300–1500\,\text{rpm}$. The AWJ turning process can be a choice of the processes for efficient material removal. Another advantage of AWJ turning is that there are no cutting tool wear problems.

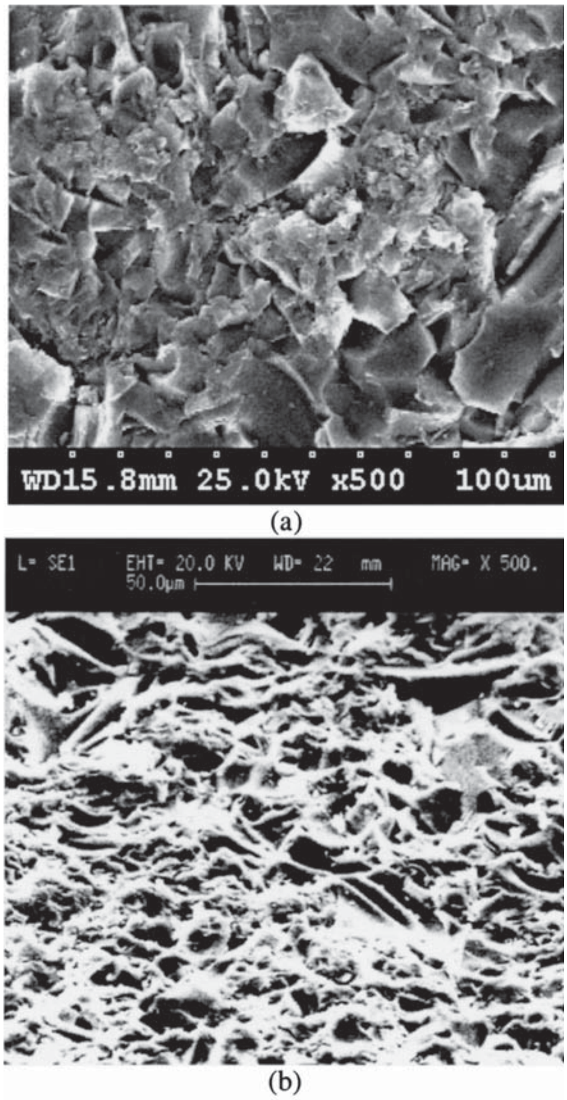

Figure 8. SEM pictures of glass surfaces machined by (a) abrasive waterjet turning, and (b) conventional grinding.

SUMMARY

Variations in surface quality achieved with some of the AWJ process settings were similar to those of the linear cutting using waterjets. For instance, higher traverse rates were associated with an increase in the material removal rate and thus an increase in the surface roughness and waviness values. The sensitivity of surface quality to rotational speed was more than that to the traverse speed. Good

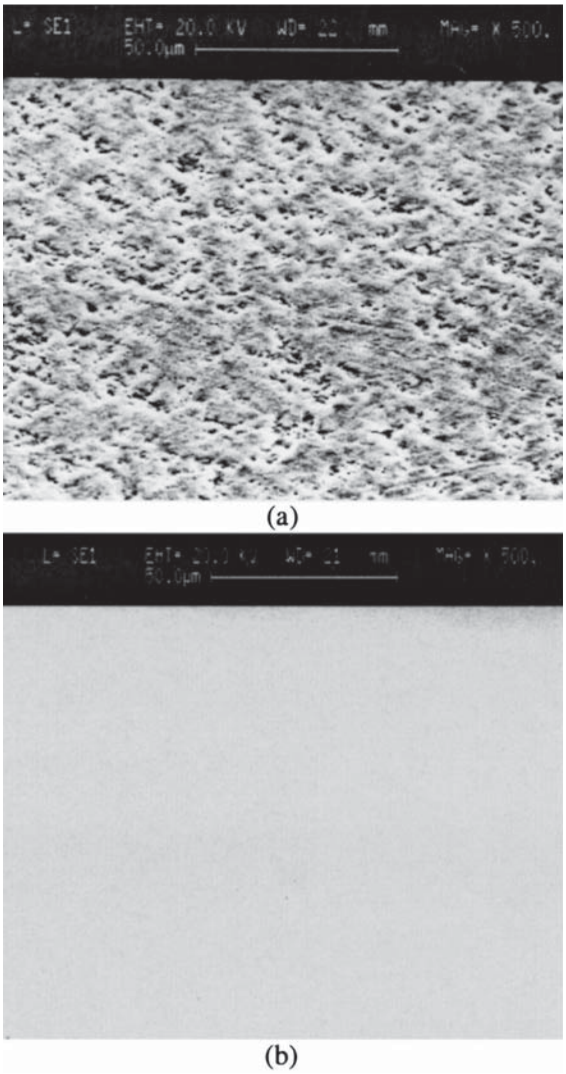

Figure 9. SEM pictures of glass surfaces machined by (a) lapping and (b) polishing.

surface finish was achieved at lower traverse speeds and higher turning speeds. Higher stand-off produced rougher surface finish. The best finish was generated when the nozzle consumed 300 g min^{-1} of abrasives. However, contrary to linear waterjet cutting, higher pressures did not produce smoother surface finish.

The glass samples machined by AWJ turning and conventional grinding are 100% fractured surfaces. The surface roughness R_a value of AWJ turned glass is much higher than those obtained from other machining processes. However, one advantage of AWJ turning is that there are no cutting tool wear problems. Another advantage is that the material removal rate can be very high for AWJ turning, as

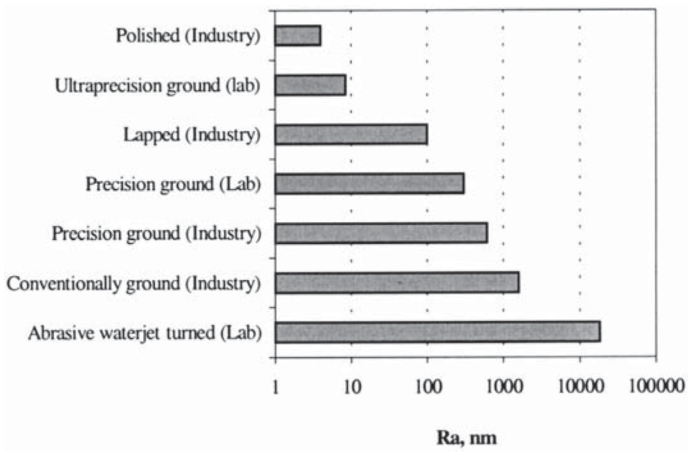

Figure 10. Surface roughness R_a of glass surfaces obtained from various processes.

the depth cut, feed rate, and rotational speed can be set at large values. The AWJ turning process can be a process of choice for efficient material removal. The disadvantages of the AWJ turning process include wear of the nozzles, its energy dissipating characteristics, and high initial capital cost.

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