Performance Analysis of Abrasive Waterjet Machining Process at Low Pressure

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Abstract. Normally, a commercial waterjet cutting machine can generate water pressure up to 600 MPa. This range of pressure is used to machine a wide variety of materials. Hence, the price of waterjet cutting machine is expensive. Therefore, there is a need to develop a low cost waterjet machine in order to make the technology more accessible for the masses. Due to its low cost, such machines may only be able to generate water pressure at a much reduced rate. The present study attempts to investigate the performance of abrasive waterjet machining process at low cutting pressure using self-developed low cost waterjet machine. It aims to study the feasibility of machining various materials at low pressure which later can aid in further development of an effective low cost waterjet machine. A total of three different materials were machined at a low pressure of 34 MPa. The materials are mild steel, aluminium alloy 6061 and plastics Delrin®. Furthermore, a traverse rate was varied between 1 to 3 mm/min. The study on cutting performance at low pressure for different materials was conducted in terms of depth penetration, kerf taper ratio and surface roughness. It was found that all samples were able to be machined at low cutting pressure with varied qualities. Also, the depth of penetration decreases with an increase in the traverse rate. Meanwhile, the surface roughness and kerf taper ratio increase with an increase in the traverse rate. It can be concluded that a low cost waterjet machine with a much reduced rate of water pressure can be successfully used for machining certain materials with acceptable qualities.

1. Introduction
The technology and applications of high pressure waterjet have been studied for many decades (as early as 1960s) [1]. It has been used extensively in various industry-related applications including machining, surface preparation, cleaning, coating removal and surface treatment or waterjet peening [2]. In general, water is compressed to an ultrahigh pressure up to about 700 MPa and discharged from a small orifice typically between 0.2 to 0.4 mm in diameter [3]. The system produces a high velocity water stream up to 900 m/s, with or without abrasive particles causing damage to materials by shearing, cracking, erosion, cavitation, delamination and plastic deformation [3]. With an addition of abrasive particles, the machining capability of the waterjet is significantly improved. A wide range of materials and thicknesses can be cut with good cutting quality and small taper. However, different processing parameters and material properties have to be carefully assessed as to produce the desired cutting qualities [4].

There has been considerable demand for a cost-effective machine tool for various industrial applications. With the advance of research and development in machine tools technology, industrial and consumer products derived from this technology are increasingly becoming commercially...
available. It is anticipated that the demand for low cost machine tools would increase considerably as their availability would make these products more affordable [5]. These machine tools will be used to produce various components. It is important to develop a low-cost versatile machine tool which is capable of preserving the structural integrity of components. Waterjet machine is one of the tools that have been considered to have potential applications for machining.

The heart of a waterjet machine is the water pump. Due to the low cost waterjet machine, the pump may have a limited capability in generating water pressure typically below 150 MPa. This range of pressure may be suitable for machining thin and soft materials. Summers et al. [6] attempted for drilling and cutting of dolomite rock at a low pressure of 35 MPa. They managed to drill the rock to a depth of 70 cm which proved effective in breaking out blocks in rock. Composite materials were also successfully machined using low-pressure pre-mixed abrasive waterjet machining process [7]. The present study attempts to investigate the performance of abrasive water jet machining process at low cutting pressure using self-developed low cost waterjet machine. It aims to study the feasibility of machining several materials at low pressure which later can aid in further development of an effective low cost water jet machine.

2. Methodology

The commercial waterjet machines available in the market are mainly used for cutting operation since they utilize high pressure mostly between 200 – 600 MPa. The heart of a waterjet machine is the water pump. The currently developed machine has a pump which can generate water pressure of up to about 100 MPa due to its low cost. The type of the pump used is an air driven liquid pump. This type of pump is reliable, compact, robust, and easy to maintain. Most importantly, the overall cost of the pump is way cheaper than the standard electrical or hydraulic type pumps which are used in a commercial waterjet machine. The machine is controlled by a computer numerical control (CNC) system. Table motion is controlled along multiple axes (X and Y) as well as the nozzle that moves in the Z-axis (depth). The cutting head consists of a ruby orifice of 0.15 mm in diameter and a tungsten carbide focusing tube of 0.76 mm and 76.2 mm in diameter and length respectively. The developed CNC waterjet machine is shown in Figure 1.

![Figure 1. The self-developed CNC waterjet machine (The inset shows the cutting process).](image)

All samples were prepared in wedge shape of 30° for easy measurement of penetration depth. They were cut using the waterjet machine according to the parametric levels as shown in Table 1. All machining procedures were conducted using a single-pass cutting. The machining performance of all cut samples was assessed in terms of depth penetration, kerf taper ratio and surface roughness. Digital Vernier high gauge was used in this experiment to measure the depth of penetration and kerf width. The tapers of the machined surfaces were measured using video measurement system (Econ). Kerf taper ratios were calculated as the ratio of top kerf width to the bottom kerf width. Three different readings for top and bottom kerf widths respectively were taken at each sample and the average
readings were calculated as to minimize the error. Finally, a surface roughness measuring device, SURFCOM130A, equipped with a cone-shaped diamond stylus having the diameter of 10 μm and tip angle of 90° was used in this study. The surface roughness was measured over the edge of the cut specimen. It was obtained across the thickness of the test sample surface. All measurements were acquired using 0.8 mm cut-off length. Due to the variability of surface finish data, three different measurements were taken for each surface evaluated so that averages could be calculated.

Table 1. List of parameters and their ranges.

| Parameter         | Range       | Unit         |
|-------------------|-------------|--------------|
| Pressure          | 34          | MPa          |
| Traverse Rate     | 1 - 3       | mm/min       |
| Abrasive          | Garnet (80) | Mesh         |
| Abrasive Flowrate | 2           | g/s          |
| Standoff Distance | 5           | mm           |
| Workpiece         | Mild Steel  |              |
|                   | Aluminium Alloy (6061-T6) | |
|                   | Plastic Delrin® (Polyoxymethylene) | |

3. Results and discussions

3.1. Effect of low water pressure on machining capability
At such an extremely low pressure (34 MPa), it is expected that the machine may be capable to cut soft materials like plastics. It is known that a higher pressure results in a higher kinetic energy of the waterjet thus giving a greater capability in causing damage for materials [8]. The kinetic energy will be great enough to accelerate the abrasive particles to hit the material and cut to a deeper depth. The depth of materials penetration increases when a higher water pressure is used. At a low pressure, its cutting capability is much reduced. Therefore, it is more suitable for an application other than cutting where a low pressure is needed for example in waterjet peening process (WJP) [2, 9]. WJP is a mechanical surface strengthening process where high-frequent impact of water drops on the surface of metal components, which causes local plastic deformation. The process is not intended to cause full penetration to the surface but rather treating the surface. It is interesting to note that based on preliminary results, using this low pressure proves that it may also cut some hard materials such as metals. However, cutting capability is very much reduced depending on the hardness of the machined materials. The depth of penetration of the materials decreases when the hardness of the material increases. Furthermore, the process has to be properly controlled in order to optimize the cutting capability of the waterjet at a low pressure. The traverse rate has to be as low as possible as to give enough time for the jet to impact the surface thus causing the penetration. Traverse rate is actually the speed of the feed motion in X or Y direction. It plays a bigger role in producing a good cutting quality.

3.2. Effect of traverse rate on penetration depth
The depth of penetration is a measure of the depth that the waterjet machining process could achieve during cutting of a material. Analysing the depth of penetration is very important as it gives an indicator about the machining performance of the process using a particular waterjet machine. The depth of penetration is not an independent issue as it varies according to different parameters. Figure 2 shows the effect of traverse rate on penetration depth for different materials. The depth of penetration increases with a decrease of traverse rate. As the traverse rate increases, the nozzle head moves faster. In this case, the waterjet with the mixture of abrasives does not have enough time to make penetration on the workpiece. The contact time between the waterjet and the material has been reduced [8]. As a result, the waterjet could not fully erode the material while the nozzle moves in a faster rate. The waterjet is only able to cut to a certain depth with a higher traverse rate.
3.3. Effect of traverse rate on kerf taper ratio

The effect of traverse rate on the kerf taper for different materials is shown in Figure 3. In general, a higher traverse rate produces a wider kerf taper ratio. The negative effect of traverse rate on the kerf width is due to the fact that a faster passing of abrasive water jet allows fewer particles to strike on the target material and, hence, generates a narrower slot [10]. In other words, the decrease in the exposure time that was caused by increasing the traverse rate resulted to the reduction in both of the kerf top and bottom width. Whereas, the increasing trend of the kerf taper ratio is the result of the more rapidly decreasing kerf width at the bottom than at the top as the traverse rate increases. Hence, the waterjet does not have enough time to penetrate through the material that leads to a wider upper kerf than the bottom kerf. However, at a higher traverse rate, its effect on the kerf taper ratio is not significant as shown in Figure 3. This result is in agreement with Azmir [11] where he found that the traverse rate was not significant in influencing the kerf taper ratio.

3.4. Effect of traverse rate on surface roughness

As shown in Figure 4, it can be seen that increasing the traverse rate produces a higher surface roughness. This is due less overlap machining actions and fewer abrasive particles to impinge the surface at a higher traverses rate thus increasing the roughness of the surface. As a result, the abrasives could not erode the target material properly thus resulting in a rough surface. At a lower traverse rate, the abrasives particles will have enough time to impinge on the target material thus producing a well penetrated cut with a smoother surface. A slower traverse rate also gives a cleaner cut with a smoother surface [1]. The roughness of the cut profiles also changes with traverse rate and it is more obvious at the highest traverse rate [12]. In this case, a lower traverse rate is desirable to produce a better surface finish as shown in Figure 4.
3.5. Machining performance for different materials

The machining performance for different materials varies depending on their types. It is known that the material properties (i.e. strength, hardness, ductility, fatigue resistance, etc.) affect their machining performance. In general, mild steel has produced the lowest values of penetration depths and followed by aluminium alloy and plastics as shown in Figure 2. This can be expected since the mild steel has the highest hardness amongst other materials. Therefore, it has a higher resistance to material removal thus producing a lower penetration depth. It is also well understood that plastics has hardness very much lower than metals. As a result, their penetration depths are many times higher than the mild steel and aluminium alloy as illustrated in Figure 2. In case of kerf taper ratio, plastics produce the highest values and followed by mild steel and aluminium alloy as shown in Figure 3. A higher value of kerf taper ratio constitutes to a lower accuracy of geometrical cut since the dimension of top width shows a higher variation with a bottom width. This is possibly due to the nature of plastics in which some fibrous particles were left during machining when the jet made an exit from the samples. Due to this nature, their surfaces are also rougher than other materials as shown in Figure 4. Furthermore, due to low hardness of plastics, its upper kerf width tends to become bigger because the jet impingement can easily erode the material thus making a bigger slot. In case of metals, lower kerf taper ratios were found since they have lower penetration depths with smoother surfaces thus resulting in more accurate cut. Aluminium alloy is softer than mild steel thus producing a higher penetration depth with a smoother surface. Examples of machined samples are shown in Figure 5 which shows their penetration depths and kerf tapers.

![Figure 4](image_url)

**Figure 4.** Effect of traverse rate on surface roughness for different materials

![Figure 5](image_url)

**Figure 5.** Examples of machined samples, a) mild steel, b) aluminium alloy, and, c) plastics

The performance of the waterjet machine during cutting of mild steel, aluminium alloy and plastics Delrin® at a very low pressure of 34 MPa are satisfactory with acceptable machining qualities. Therefore, it would be interesting to further test its capability by machining other materials. Ceramic tiles and glass were chosen for further experiment. Machining of ceramic tiles at a pressure of 34 MPa and traverse speed of 5 mm/min produced a surface roughness of 4.591 µm and penetration depth of 8.7 mm. On the mild steel and ceramic tile surfaces, an obvious wavy pattern or waterjet lagging can be clearly observed as shown in Figure 6. In case of glass machining at low pressure of 34 MPa, the glass surface has experienced slight chipping due to its brittleness. When the pressure had increased to
69 MPa while maintaining the traverse rate, the waterjet was able to cut through the glass without any crack or chipping as shown in Figure 6. This is possibly due to sufficient energy of the jet to cause smooth erosion to the glass.

![Image of machined samples](image)

**Figure 6.** Examples of machined samples, a) mild steel, b) ceramic tile, and, b) glass

### 4. Conclusions

It was shown that mild steel, aluminium alloy 6061 and plastics Delrin® were successfully machined at low cutting pressure using self-developed low cost waterjet machine. The cutting performance of the waterjet machine is satisfactory with acceptable machining qualities. The depth of penetration decreases with an increase in the traverse rate. Meanwhile, the surface roughness and kerf taper ratio increase with an increase in the traverse rate. It can be concluded that the self-developed waterjet machine with a much reduced rate of water pressure can be successfully used for machining some materials with acceptable qualities.

### 5. Acknowledgments

Authors would like to gratefully acknowledge the financial support from the Universiti Malaysia Pahang through RDU140128 and RDU150347.

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