Machining of different materials with abrasive waterjet cutting

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Abstract. Aim of the paper is summarization of some result in the field of waterjet cutting on different materials, like steel, ceramic and polymer. Cutting experiments were accomplished to investigate the efficiency and the accuracy of the cut while machining of mentioned materials. From the result there are conclusions drawn up on the extent of technological parameters like feedrate, abrasive mass flow and the pressure.

1. Introduction
Modern waterjet cutting machine tools can adjust technological parameter of the cut almost automatically. Final user does not know why these parameters are applied. Usually these parameters are overestimated and not economical. That is why the knowledge of the choice of technological data is important nowadays as well. We need to choose the parameters with good efficiency, but according to the prescribed accuracy of the cut.

Efficiency and quality of the water jet cutting process can be characterised by different output parameters, like surface roughness of the machined surface, geometry of cutting kerf (depth, width, tapering). Depth of kerf is one of the most typical parameters for describing the efficiency of the cutting process. When making kerfing tests we do not cut through the material but produce a kerf only (Fig. 1).

Figure 1. Kerfing test in glass material.
There are a lot of technological parameters which effect on the efficiency of waterjet cutting: diameter of the nozzle and the focusing tube, type of abrasive, stand-off-distance, pressure, traverse rate, abrasive mass flow rate etc. Recent research is focused to investigate the effect of the next process parameters: pressure, traverse speed (feed rate) and abrasive flow. Other parameters are considered constant and their value should be determined on basis of the knowledge exchange and technical possibilities of the project partners.

When cut through the material, one of the limit of application of waterjet cutting are the different accuracy problems of this machining method. Usually the form of the cutting kerf causes difficulties in the assurance of the prescribed accuracy. Form of the kerf is always very complex, but basically it can be considered like two tapered plains (Fig.2.). [1]

Kerf characteristics refer to the kerf geometrical features as kerf width, kerf taper and kerf depth. The surface topological features as represented by surface roughness and striation (or waviness) are also to as kerf characteristics. Generally, there are two types of kerfs, through cut and non-through cut. The typical geometry of a through cut kerf is shown in Fig. Error! Reference source not found. It has a wider entry and its width decreases as the jet cuts into the material, so that a kerf taper is produced. In most cases the kerf is wider at the upper side (entering) then the lower side, where the jet goes out from the workpiece, so the taper can be convergent ($w_t > w_b$), divergent ($w_t < w_b$) or even divergent-convergent.

![Figure 2. Taper of the kerf.](image)

Kerf taper is normally expressed by kerf taper angle as [2]

$$\theta = \arctan\left(\frac{w_t - w_b}{2t_n}\right)$$

(1.1)

where $w_t$ is the top kerf width, $w_b$ is bottom kerf width, $t_n$ is workpiece thickness for through cuts.

Taper of cut was investigated by more authors [3][4][5] but the conclusions are sometimes controversial.

Aim of recent research work was to get connections between the technological parameters and the taper of the kerf for finding cutting parameters with which we can get parallel cut surface.

2. Experimental conditions

We carried out two types of cutting tests. Kerfing tests (not through cut) were made for investigation of efficiency and cut through test were done for investigation of taper angle of the cut.

Main parameters and characteristics of the tests are shown in Table 1. During the experiments we changed the water pressure ($p$), the abrasive mass flow rate ($m_a$) and the feedrate (feed) speed ($v_f$). Other parameters can be considered constant.
Table 1. Characteristics and parameters of the cutting experiments.

| Characteristic                      | Kerfing test                  | Cut through test            |
|------------------------------------|--------------------------------|-----------------------------|
| Type of machine tool               | OMAX 120X                      | INNO PUMP-36HD              |
| Workpiece material                 | S235JR construct. steel        | AlMgSi0,5 Al-alloy          |
|                                    | Polyvinylchloride PVC          | Polyethylene HDPE           |
|                                    | White marble                   | S355J2 construct. steel     |
| Thickness of the material [mm]     | is not characteristic          | 10                          |
| Diameter of water nozzle [mm]      | 0.41                           | 0.25                        |
| Diameter of abrasive nozzle [mm]   | 1.07                           | 0.8                         |
| Stand of distance [mm]             | 2                              | 2                           |
| Abrasive mass flow rate [g/min]    | 320,550                        | 28, 68                      |
| Water pressure [bar]               | 1380, 2500, 3590               | 2000, 2500, 3000, 3500      |
| Feedrate speed [mm/min]            | 100, 120, 140, 160, 180, 200   | 50, 100, 150, 250, 300      |
|                                    | 1000, 1400, 1800, 2200, 2600   | 100, 500, 1000, 1500, 2000  |
|                                    | 650, 750, 850, 950, 1050       | 20, 40, 60, 80, 100         |

After the cutting experiments depth of kerf (k), upper width (w_u) and lower width (w_b) of the kerf were measured for determination of the depth and taper of the kerf.

Measurements of the kerf width were accomplished on a stereo microscope type ZEISS SteREO Discovery.V8 (Fig. 3).

Figure 3. Measurement of the kerf with at the upper and the bottom side on microscope ZEISS SteREO Discovery.V8 (material: S355J2 steel).
3. Experiments for investigation of efficiency

Cutting through test (kerfing tests) were carried out on materials presented in Table 1. Constructonal steel test part can be seen in Fig. 4. It is easy to see the different depth of the kerf machined by different technological parameters.

![Figure 4. Kerfing test in S235JR steel.](image)

Like an example, effect of the technological parameters on the depth of kerf (efficiency of the cut) is presented on Fig. 5 in case of PVC material.

![Figure 5. Influence of the pressure on the depth of kerf at different feed speed in PVC](image)

From Fig 5 we can see that increase of the pressure increases the depth of cut and increase of the feed speed decreases it. Effect of the pressure is almost linear. At lower pressures the effect of the feed speed higher, then at high pressures. The inclination angles of the lines are higher at low pressure. This could be explained by the effect of the loading time. Increasing the feed speed the loading time is decreasing, so the higher speed of the abrasive grains – coming from the higher pressure - in the jet cannot affect totally the material removal rate. Similar trends were experienced at the marble and the steel as well.

Effect of the feed speed and the comparison of different materials can be seen on Fig. 6. From the figure we can see that the effect of the feed speed (traverse speed) is not linear, it shows exponential or power function characteristics. More interesting conclusions can be drawn by comparing the different materials.
Figure 6. Influence of the feed speed on the depth of kerf at different materials

From Fig. 6 we can explain, that most difficult to cut material is the steel and most easy is the marble. This is a little bit surprising, since aluminum alloy has the least hardness. Easier to cut a material, if the inclination angle of its curve on Fig 6 is smaller. This phenomenon can be explained with the different type of erosion process of the materials. Steel and aluminum alloy have so called ductile erosion, which is typical for ductile metals, while marble has a so called rigid erosion, which is characteristic for ceramics. If any of these two processes can be happened easy, the material is easy to cut.

4. Experiments for investigation of quality (kerf angle)
We carried through tests for investigation of taper angle of the kerf interpreted on Fig.2. On Fig. 7 we can see the test part from PVC.

Figure 7. Kerfing tests on PE material

Main parameters and characteristics of the tests are shown in Table 1. During the experiments we changed the water pressure (p), the abrasive mass flow rate (ma) and the feederate speed (v_f). After the tests we measured the with on the top and the bottom side of the kerf (Fig. 3).

Effect of the feed speed and the water pressure on the width of the kerf (on the upper and the bottom side) can be seen on Fig. 8. From the figure easy to accept that the width of the upper side of the kerf decreases barely in function of the feed speed. At the bottom side of the kerf the decrease is much higher. This cause the taper angle of the cut kerf.
Figure 8. Effect of feed speed and the water pressure on the width of the kerf at the top and bottom side in case of PE material

Increase of the pressure basically increases the width of the kerf (Fig. 8.). It is interesting to observe that change from 3000 to 3500 bar causes minimal change in the width but change from 2500 to 3000 bar causes high change in the value of widths.

From the widths on the top and bottom side the value of the kerf angle can be calculated (1.1). Change of the calculated angles in function of feed speed and pressure can be seen on Fig. 9.

Figure 9. Effect of feed speed and the water pressure on the angle of the kerf in case of PE material

Increase of the feed speed increases the angle of the kerf, that is increases the inaccuracy of the cut. The effect of the pressure is not completely clear according to the literature [6][7][8][9]. Usually the
increase of the pressure decreases the angle of the kerf while the width of the kerf increases. This statement cannot be substantiated by these experiments.

On Fig 10. we can compare the characteristics of different materials.

![Figure 10. Effect of feed speed on the angle of the kerf in case of different material](image)

5. Conclusions

The following conclusions can be drawn from the experiments carried out for the investigation of cutting depth and taper angle of the kerf at waterjet cutting different materials:

- From the technological parameters the increase of the feedrate speed clearly and significantly reduces the depth of kerf that is the efficiency of the cut. However, increasing of feed speed decreases the machining time, so it is cost effective.

- Effect of the water pressure is clear. The pressure increases the depth of cut. Same effect has the abrasive flow rate. The pressure can affect efficiently if the feed speed is relatively small, because in this case there is enough time for the interaction between the jet and the workpiece. From point of view of efficiency, the pressure and the mass flow rate should be chosen as high as it is allowed by the different restrictions.

- From results of cut different materials it can be established, that steel is the most difficult to cut. Cutting of the PVC and the marble are similar in a given interval, but the PVC can be cut with very high feed speed too. This can be explained by the easy rigid erosion of the marble and easy ductile erosion of the PVC.

- On base of the cutting experiments we can point out that the accuracy of the cut surface is basically defined by the size and form of the cutting kerf. Cutting kerf is usually tapered, orientation of the taper mainly depends on the quality of machined material, at metals it is usually convergent.
The extent of the kerf angle basically depends on the technological parameters. The feed speed \((v_f)\) clearly increases the taper angle of the kerf. The effect of the water pressure \((p)\) and the abrasive mass flow rate \((m_a)\) could strongly effect on the taper mainly at lower feedrates, when there is enough loading time for the abrasive particles to remove the material from the workpiece.

Comparing the cut of different materials, can be established that taper angle of steel is higher than at aluminum alloy or PE polyethylene. In all cases the increase of the feedrate speed increases the angle of the kerf (inaccuracy), but slopes of the curves of each material are very different. Near parallel cut can be reached in case of PE polyethylene.

From the results it can be established that the extent of taper angle and the depth of the kerf basically depends on the quantity of the energy-input and can be controlled by it. So future researches will have oriented to describe connections between the loading energy and the cut kerf geometry.

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