EFFICIENCY OF MACHINING POLYMER, MARBLE AND STEEL MATERIALS AT ABRASIVE WATER JET CUTTING

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Abstract
In recent decades, waterjet cutting technology has become widespread across various industries worldwide, ranging from automotive and insulation manufacturing to aerospace. Concurrently, it's increasingly important for the applied technological parameters to be efficient and cost-effective. This necessitates the appropriate selection of key technological parameters. In this article, we examined the efficiency of abrasive waterjet cutting in three different material qualities: polymer, ceramic, and steel. The article explores the relationship between cutting depth—considered as one widely accepted indicator of efficiency—and technological parameters, drawing conclusions regarding the machinability of various materials.

Keywords: *abrasive waterjet cutting, depth of kerf, efficiency, technological parameters*

1. Introduction

The efficiency of abrasive waterjet cutting is typically assessed by researchers through the examination of the depth of kerf (k). During kerfing experiments, the material is not cut through its entire cross-section; instead, a certain depth of cut is made into the material. This depth of kerf depends on the set technological parameters and other conditions of waterjet cutting. The interpretation and measurement of the depth of kerf are illustrated in *figure 1.*

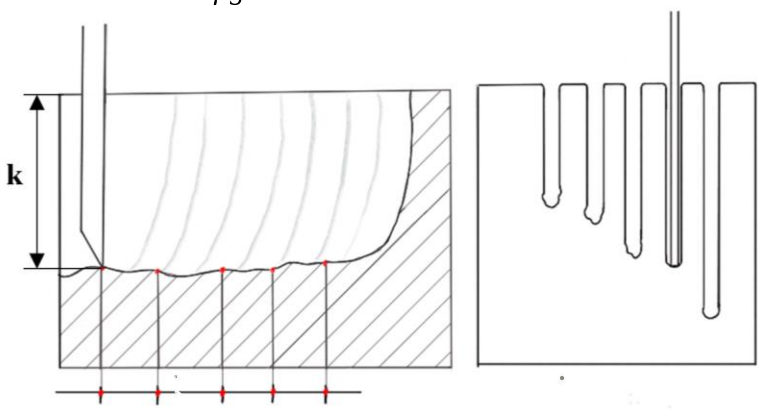


Figure 1. *Interpretation and measurement of depth of kerf*

Abrasive waterjet (AWJ) technology is known for its versatility and its capability to cut a wide array of materials, including challenging-to-cut metals, ceramics, and polymers (Llanto, 2021). The literature extensively examines the magnitude of the achievable depth of kerf with specific parameters for various machined materials. The depth of cut in abrasive waterjet cutting is influenced by various parameters such as water pressure, abrasive flow rate, jet traverse rate, and standoff distance (Selvan at al., 2022; Sun at al., 2023; Pon at al., 2018). Studies have focused on technological parameters like feed speed, abrasive mass flow, and pressure to investigate the efficiency and accuracy of the cut while machining different materials (Chen at al., 2023; Yu at al., 2020; Chen at al., 2023; Panchal at al., 2022).

The aim of this research is to determine how the technological parameters of abrasive waterjet cutting affect the efficiency of cutting for three different material qualities.

2. Experimental conditions

Kerf cutting experiments were conducted on three significantly different material qualities: white marble, polyvinyl chloride (PVC) and steel. During the experiments, the changed parameters were feed speed (v_f), pressure (p) and abrasive mass flow rate ($\dot{m}$). The range of investigation for these technological parameters was determined based on preliminary experiments [9].

The experiments were performed using an OMAX 120X type abrasive waterjet cutting machine *(Figure 2)*. The maximum size of the workpiece that can be placed on the equipment is 3100 mm × 6100 mm, and the maximum size that can be processed is 2948 mm × 6040 mm. The inner diameter of the water nozzle used for cutting was Ø 0.41 mm, that of the abrasive nozzle was Ø1.07 mm.

Garnet #80 type garnet powder was used as an abrasive material for the kerf cutting experiments. Garnet is a collective name for silicates that crystallize tetrahedrally, e. g. compounds of Mg, Ca, Fe. Although a variety of abrasive powders can be used for abrasive waterjet cutting, e. g. olivine (Fe_2SiO_4), aluminium oxide (Al_2O_3), silicon carbide (SiC), zirconium, quartz sand, etc. yet garnet powder is used, almost everywhere in the world. This can be explained by the cost-effectiveness and technological suitability of garnet powder.

The GARNET #80 powder used for experiments has a reddish-brown colour *(Figure 3)*. The particle size in the powder ranges up to 150–300 µm, with a density of 2.43 g/cm^3, a hardness of 7.5–8 on the Mohs scale, and a melting point of 1250 °C.

Figure 2. *OMAX 120X type waterjet cutting machine*

Figure 3. *GARNET #80 abrasive powder abrasive (grains)*

2.1. Machined materials

Qualities investigations were carried out on materials significantly different in their properties:

- White marble (Carrara marble),
- PVC (polyvinyl chloride),
- S235JR general-purpose non-alloy structural steel (MSZ EN 10025).

White marble is a rock transformed from chemical sedimentary limestone. Pure marble contains more than 95% calcite. Its structure is dense and granular. White marble is the purest and most valuable marble, but its colour can vary greatly due to impurities or inclusions: gray, yellow, red, blue, black. The colours can be uniform or veined, spotted, cloudy. The characteristic compressive strength of white marble is 90–150 MPa, with an elasticity modulus of 50–70 GPa, and a hardness of 3.5 on the Mohs scale, equivalent to approximately 229 HV hardness. For the experiment, a 50 mm thick white marble piece was used.

PVC (polyvinyl chloride) is a thermoplastic, combustible, chemically resistant, hard, amorphous plastic. It is the third most produced synthetic polymer in large quantities. Polyvinyl chloride is produced from vinyl chloride, mostly through suspension or bulk polymerization. Currently, two types are used: rigid and plasticized PVC. In the technical field, plasticized PVC is predominantly used. The characteristic tensile strength of soft PVC is 15 MPa, with a density of 1.2 g/cm^3, and a melting temperature of 140 °C. The workpiece used was a 40 mm thick PVC.

S235JR general-purpose non-alloy structural steel is an excellent weldable, machinable, and cold-formable non-alloy structural steel. Its chemical composition is shown in *table 1*.

Table 1. *Chemical composition of S235JR unalloyed structural steel*

Alloy	**C, %**	**Si, %**	**Mn, %**	**P, %**	**S, %**	**Cu, %**	**N, %**
S235JR	0,17…0,2	≤ 0,3	≤ 1,4	≤ 0,045	≤ 0,045	≤ 0,4	≤ 0,012

Its characteristic tensile strength R_m = 340–510 MPa, yield point R_{eh} = 225–235 MPa, and specific elongation at fracture 21–26%. The experimental piece was a 40 mm thick rolled sheet.

2.2. Technological parameters

Among the technological parameters that influence efficiency, we examined the effect of feed speed, pressure, and abrasive flow rate (the mass of abrasive material per unit time added to the water jet). The values of these parameters were varied within predetermined ranges based on preliminary experiments. Other parameters such as the type of abrasive material, nozzle height, abrasive nozzle and water nozzle diameter were kept constant throughout, i.e., the water nozzle diameter was 0.41 mm, the abrasive nozzle diameter was 1.07 mm, and the nozzle height was 2 mm. Garnet #80 abrasive powder was used. The values of the varied technological data *(Table 2)* were determined based on literature and empirical data, as well as the capabilities of the machine (Maros, 2018).

Table 2. *Technological parameters*

Changing parameters	White Marble	PVC	S235JR
Pressure [bar]	1380–2500–3590	1380–2500–3590	1380–2500–3590
Feed speed [mm/min]	650–750–850–950–1050	1000–1400–1800–2200–2600	100–120–140–160–180–200
Abrasive mass flow [g/min]	320–550	320–550	320–550

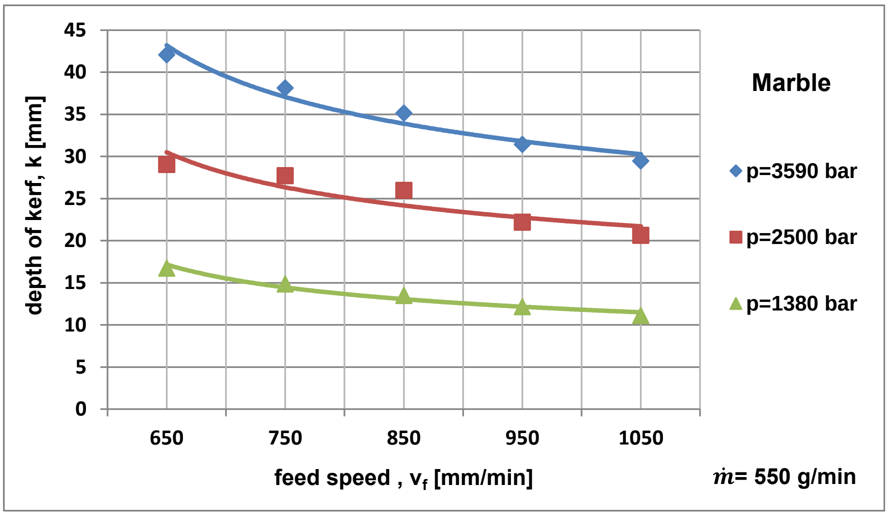
3. Experimental results

As an example, the kerfs cut made on white marble are shown in *figure 4*. After conducting the experiments, we measured the depths of cuts for all three material qualities.

Figure 4. *Kerfs cut made on white marble*

3.1. White marble

The variation of cutting depths in white marble as a function of feed speed is shown in *figure 5*.



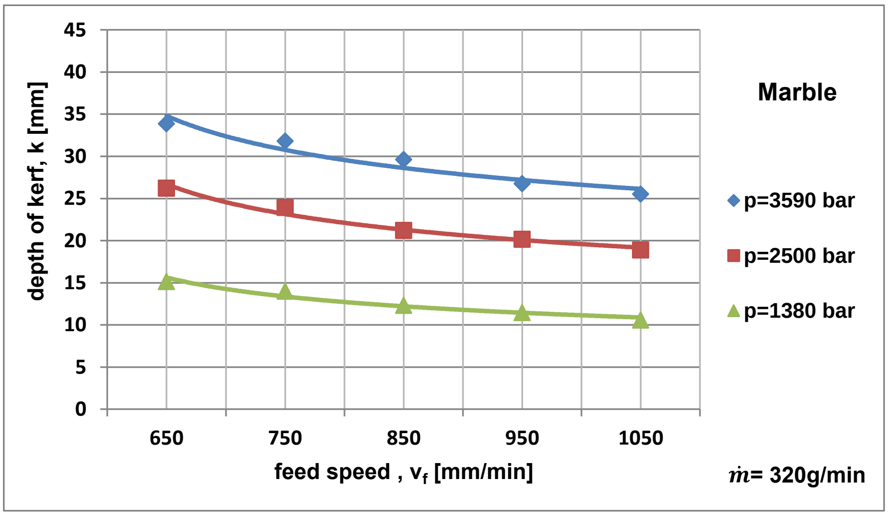


Figure 5. *Effect of feed speed on depth of kerf at different pressures and abrasive mass flow rate on white marble material*

From *figure 5*, it can be observed that increasing the feed speed reduces the depth of kerf. Increasing the pressure clearly increases the magnitude of the depth of kerf, i.e., the efficiency of cutting. The cuts made at the highest pressure with the smallest feed speed result in the greatest cutting depth. However, as the feed speed increases, the difference in the effects of different pressures decreases. It can also be seen that cutting with a smaller abrasive material flow produced a smaller depth of cut in all cases for higher abrasive flow rates, the steepness of the curves in the graph is greater compared to lower values.

3.2. Polyvinyl Chloride (PVC)

The results of cutting experiments on PVC are shown in *figure 6*.

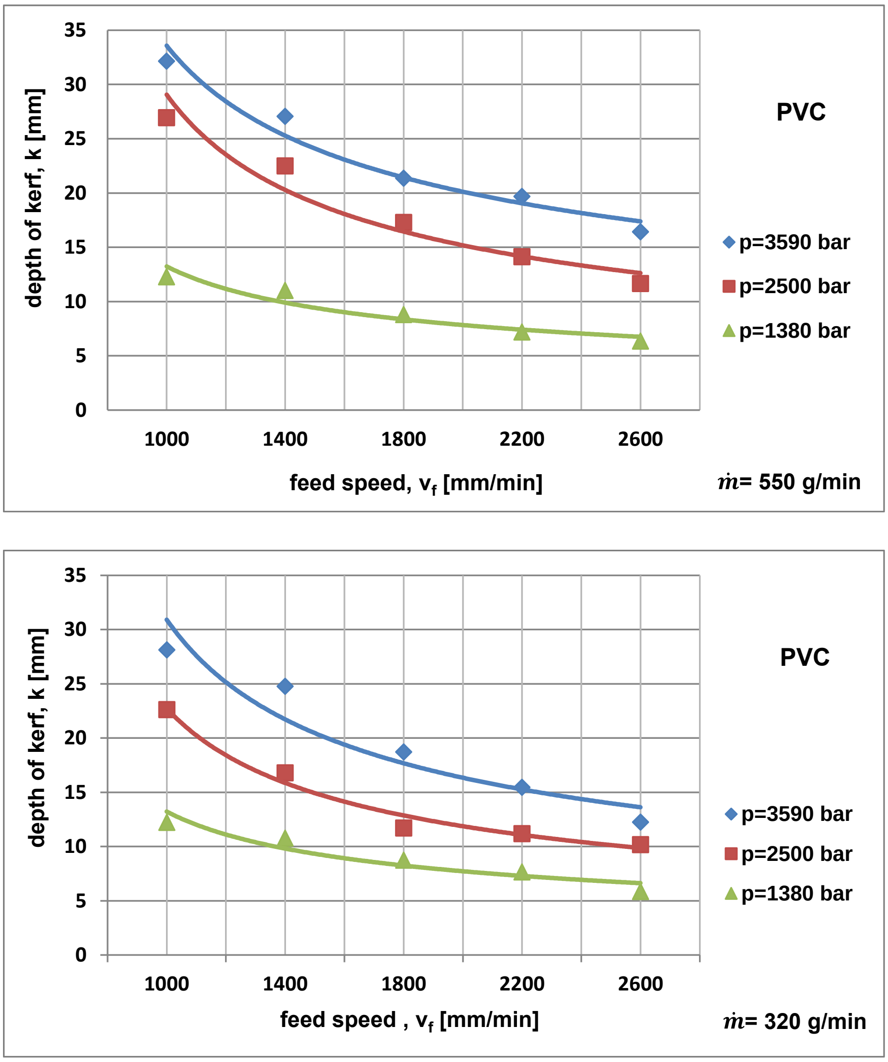


Figure 6. *Effect of feed speed on depth of kerf at different pressures and abrasive mass flow rate on PVC*

The variation of the feed speed is also significant for PVC material. Increasing it decreases the depth of kerf *(Figure 6)*. The differences between pressures are most dominant at lower feed speeds. The differences between cuts are greater than in marble. At lower pressures, the effect of the feed speed is less pronounced, meaning the steepness of the curves decreases. Decreasing the abrasive flow rate resulted in shallower cuts at a given pressure. This effect is most noticeable when using higher pressures.

3.3. Structural steel

The results of cutting experiments on S235JR structural steel are illustrated in *figure 7*.

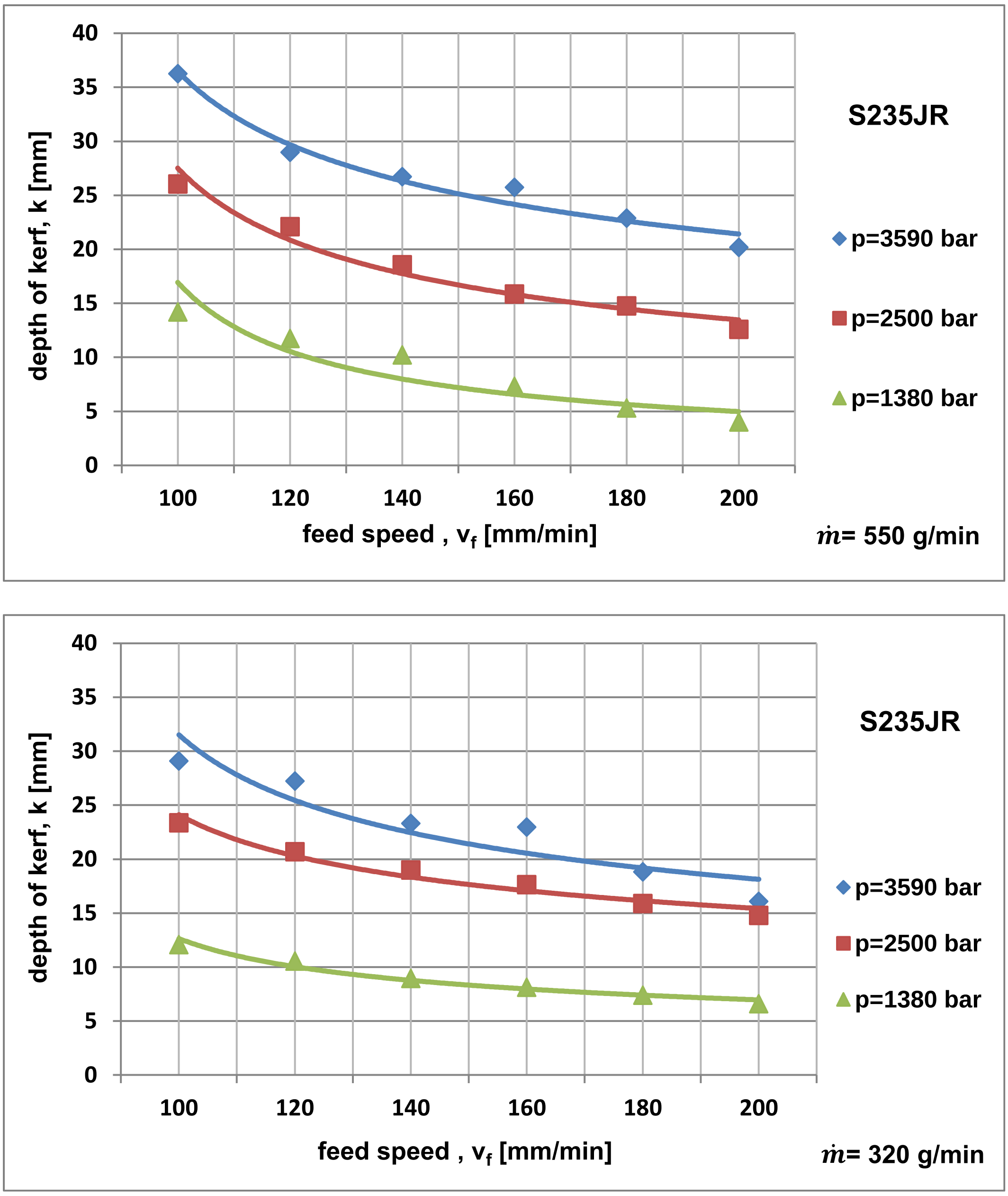


Figure 7. *Effect of feed speed on depth of kerf at different pressures and abrasive mass flow rate on S235JR structural steel*

From *figure 7*, it can be seen that increasing the feed speed clearly reduces the cutting depth for steel. In this case, the greatest cutting depth was achieved with the smallest feed speed for all three pressures. At lower abrasive flow rates, the effect of pressure is less dominant, as shown in the lower part of *figure 7*, where the curve at 2500 bar is much closer to the curve at 3590 bar. The effect of pressure is most pronounced when using higher abrasive flow rates and smaller feed speeds. In such cases, increasing the pressure clearly increases the cutting depth. At a given pressure, smaller abrasive flow rates result in shallower depth of kerf.

3.4. Comparison of different material qualities

The variation of depth of kerf as a function of feed speed for different material qualities is shown in *figure 8*.

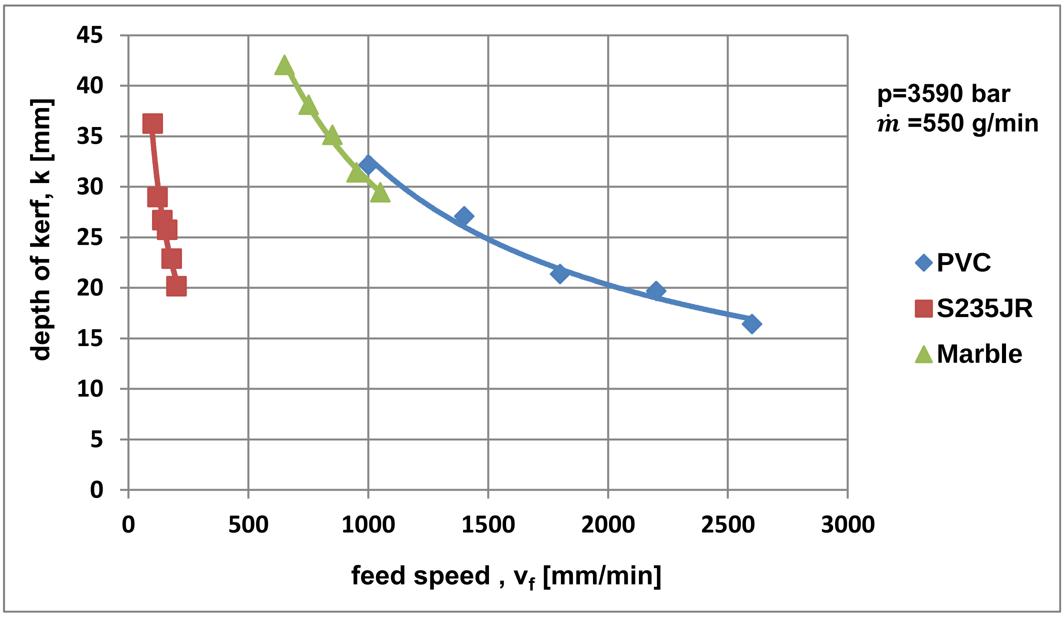


Figure 8. *Effect of feed speed on depth of kerf on different material qualities*

From *figure 8*, it can be concluded that steel is the most difficult to cut. PVC and marble can be cut with almost equal efficiency within the investigated range of technological data, which is surprising considering that marble is harder than PVC. The explanation for this lies in the fact that marble undergoes rigid erosion since it is a rigid material, while PVC's material removal occurs through relatively easily initiated tough erosion. For example, a 30 mm depth cut at the same pressure and the same abrasive flow rate can be achieved at approximately 120 mm/min on steel, about 1000 mm/min on marble, and about 1100 mm/min feed speed on PVC.

4. Conclusions

Based on the evaluation of experimental results, the following general conclusions can be drawn:

- Among the technological parameters, increasing the feed speed clearly and significantly reduces the cutting depth, i.e. cutting efficiency.
- The effect of pressure is also evident, with an increase in water pressure leading to an increase in depth of kerf. However, pressure primarily exerts its effect at low feed speeds when there is time for material removal. At higher feed speeds, the dominance of pressure’s effect diminishes.

- The magnitude of abrasive flow rate increases the depth of kerf, hence the cutting efficiency, especially noticeable with low feed speeds and high pressure values.
- The results of cutting different materials show that steel is the most difficult to cut.
- The machinability of marble and PVC materials can be considered nearly equal. PVC material slightly outperforms marble. This close value, considering the hardness of the two materials, is surprising and can be attributed to the rigid erosion mechanism of marble and the relatively easily initiated tough erosion mechanism of PVC. However, it can also be stated that the machinability of marble and PVC materials significantly surpasses that of steel.

Based on the conclusions drawn from the results, recommendations can be made for increasing efficiency on different experimental materials, as well as for the machinability of typical material types and the selection of technological data for specific cutting tasks. Possible further directions for research could involve seeking mathematical relationships between the investigated efficiency characteristics and machining parameters, or analysing how these parameters affect surface quality, accuracy, and surface roughness.

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