

INVESTIGATION OF ENERGY INPUT AND MACHINING EFFICIENCY AT ABRASIVE WATER JET CUTTING

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Abstract. *Abrasive waterjet machining is a widely used technology for cutting metal, ceramic and polymer sheets. Nowadays, it is becoming important that the applied technological parameters are efficient and economical. This requires the appropriate selection of the most important technological parameters. In this paper, we report on research in which the combined effect of technological parameters, i.e. the relationship between the input energy and the efficiency, was examined when machining three material qualities (metal, ceramic, polymer). The article examines the relationship between the depth of kerf and the amount of energy input by the jet and formulates conclusions regarding the machinability of different materials.*

Keywords: *abrasive waterjet machining; technological parameters; cutting energy; input energy.*

1. Introduction

The efficiency of abrasive waterjet cutting is most often characterized by researchers [1] with the so-called kerfing depth. When making kerfs, the material is not cut across its entire cross-section, but a certain depth of kerf is made in the material. This type of investigation is referred to as a kerfing test. The depth of kerf depends on the set technological parameters and other conditions of waterjet cutting. The interpretation and measurement of the depth of kerf is illustrated in Figure 1. Abrasive waterjet cutting can machine a wide range of materials, including difficult-to-cut metals like ceramics and polymers. The literature extensively studies the depth of kerf achievable as a function of process parameters [2,3,4]. The depth of kerf of abrasive waterjet cutting is influenced by various parameters, such as water pressure, abrasive flow rate, feed speed, nozzle height, and nozzle geometry [5,6,7]. Researchers primarily investigate the efficiency and accuracy of cutting in relation to these parameters when machining different materials [8,9,10,11].

The effect of the energy input by the jet on the cutting efficiency has been studied by few researchers, mostly through theoretical studies [12]. The aim of this

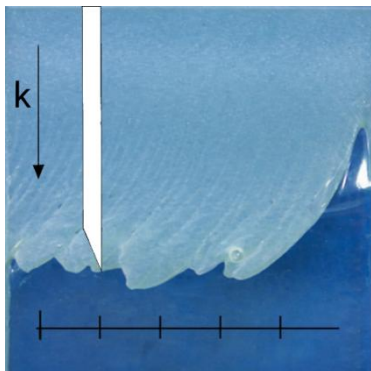


Figure 1 – Interpretation and measurement of kerf depth

research is to determine how the amount of energy input by the jet into the material during abrasive waterjet cutting affects the depth of kerf, i.e. the efficiency, when cutting different materials.

2. Theoretical energy of the jet

The combined effect of the technological parameters can be examined by determining the theoretical energy of the beam during the various parameter settings. For this, we need to write down the theoretical kinetic energy represented by the beam and introduced into a given point on the entry side of the workpiece, which can be determined in the simplest way as follows:

$$E_m = \frac{m_a \cdot v^2}{2} \quad (1)$$

where m_a : mass of abrasive added to the during the contact time, kg
 v : velocity of the flowing particles, m/s

The actual energy of the beam is of course not exactly this value, because it is influenced by a lot of factors - the beam does not consist only of abrasive particles, the speed and size of the particles are not the same, etc. - but this value is proportional to the real energy of the beam.

According to the simplified Bernoulli equation, the velocity of the water flowing out of the nozzle is:

$$v = \sqrt{\frac{2p}{\rho}} \quad (2)$$

where p : applied pressure, Pa
 ρ : density of the water (1000 kg/m³)

Mass of the abrasive powder:

$$m_a = \dot{m} \cdot t_a \quad (3)$$

where \dot{m} : extent of abrasive flow rate, kg/s
 t_a : the time of impact, s (the time the jet is in contact with a given point)

Considering that the exposure time:

$$t_a = \frac{d_m}{v_f} \quad (4)$$

where d_m : diameter of the abrasive nozzle, m
 v_f : feed speed of the cutting head, m/s

Combining equations (1)-(4) yields that

$$E_m = \frac{\dot{m} \cdot d_m \cdot p}{\rho \cdot v_f} \quad (5)$$

Using equation (5), we determined the theoretical energy of the abrasive water jet for each technological parameter setting during the experiments.

3. Experimental conditions

3.1 Machined materials

Our tests were conducted on materials with significantly different properties:

- White marble (Carrara marble).
- General purpose structural steel S235JR.
- PVC (polyvinyl chloride).

White marble is a chemically metamorphosed rock from sedimentary limestone. Pure marble contains more than 95% calcite. Its structure is dense and granular. The typical compressive strength of white marble is 90–150 MPa, its modulus of

elasticity is 50–70 GPa, and its hardness on the Mohs scale is 3.5, which corresponds to a hardness of approximately 229 HV. A 50 mm thick piece of white marble was used for the experiment.

S235JR general purpose unalloyed structural steel is an unalloyed structural steel with excellent weldability, machinability and cold forming properties. Its chemical composition is shown in Table 1.

Table 1 –Chemical composition of unalloyed structural steel S235JR

Material	C, %	Si, %	Mn, %	P, %	S, %	Cu, %	N, %
S235JR	0.17–0.2	≤ 0.3	≤ 1.4	≤ 0,045	≤ 0,045	≤ 0,4	≤ 0,012

The typical tensile strength of S235JR steel is $R_m=340–510$ MPa, yield strength $R_{eh}=225–235$ MPa, and specific elongation at break is 21–26%. The test piece was a 40 mm thick rolled plate.

PVC (polyvinyl chloride) is a thermoplastic, flammable, chemically resistant, hard, amorphous plastic. It is the third most mass-produced synthetic polymer. The typical tensile strength of soft PVC is 15 MPa, the density is 1.2 g/cm³, and the melting point is 140 °C. The workpiece used was 40 mm thick PVC.

3.2 Technological parameters

Among the technological parameters influencing the efficiency, the effect of the feed speed (v_f), the pressure (p) and the abrasive flow (m_a) – the mass of abrasive powder added to the water jet per unit time – was investigated. The values of these parameters were changed within predetermined ranges based on the conducted preliminary experiments. The other parameters, such as the type of abrasive material, the height of the nozzle, the diameter of the abrasive and primary nozzles, were kept unchanged throughout. The values of the changed technological data (Table 2) were determined based on literature and empirical data [13].

Table 2 – S235JR Technological parameters changed during the cutting experiments

White marble	
Water pressure, p [bar]	1380 – 2500 – 3590
Feed speed, v_f [mm/min]	650 – 750 – 850 – 950 - 1050
Abrasive flow, m_a [g/min]	320 - 550
S235JR	
Water pressure, p [bar]	1380 – 2500 – 3590

Feed speed, v_f [mm/min]	100 – 120 – 140 – 160 – 180 – 200
Abrasive flow, m_a [g/min]	320 - 550
PVC	
Water pressure, p [bar]	1380 – 2500 – 3590
Feed speed, v_f [mm/min]	1000 – 1400 – 1800 – 2200 - 2600
Abrasive flow, m_a [g/min]	320 - 550

The diameter of the primary nozzle was 0.41 mm, the diameter of the abrasive nozzle was 1.07 mm, and the height of the nozzle was 2 mm. Garnet #80 abrasive powder was used. In industrial practice, this is the most commonly used abrasive type in abrasive waterjet cutting.

Figure 2 shows the kerfs made in the S235JR structural steel material during the experiments.



Figure 2 – Results of kerf tests on S235JR structural steel

4. Experimental results

After performing the cutting experiments on marble, steel and PVC materials, we measured the cutting depth corresponding to the given parameter combinations and illustrated the change in the cutting depth as a function of the different combinations of the changed parameters. Figure 3 shows the change in the depth of kerf as a function of the feed speed and pressure with two types of applied abrasive flows, on white marble material.

It can be seen from Fig. 3 that increasing the feed speed reduces, and increasing the pressure and abrasive flow increases, the depth of kerf.

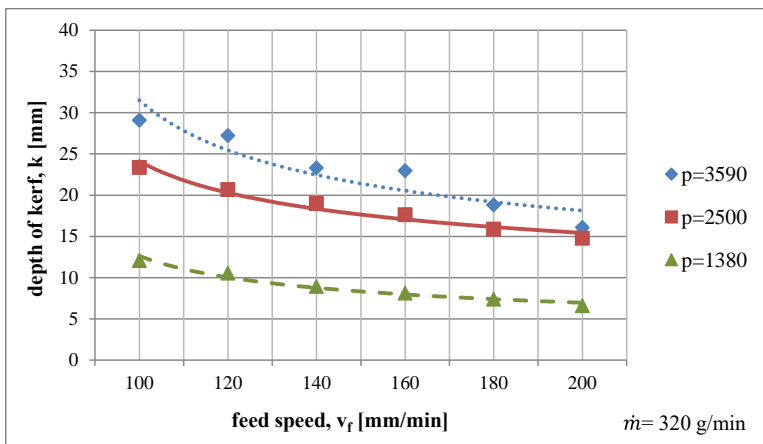
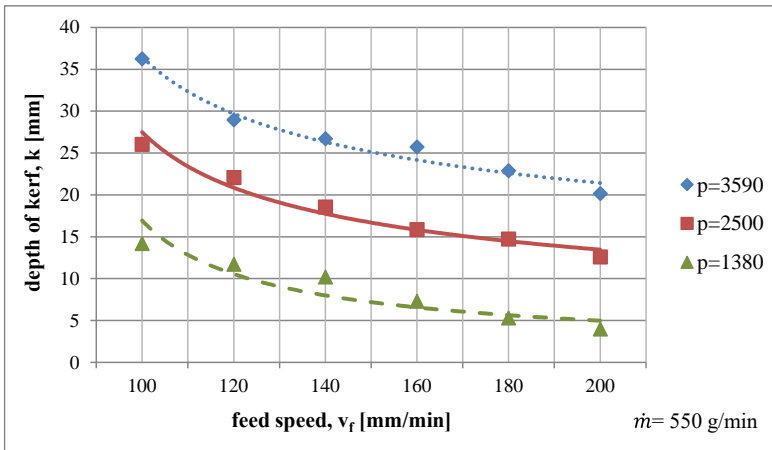


Figure 3 – Variation of depth of kerf as a function of feed speed at different pressures and abrasive flow on S235JR structural steel

Figure 4 illustrates the machinability of the three tested material qualities at a given pressure and abrasive flow.

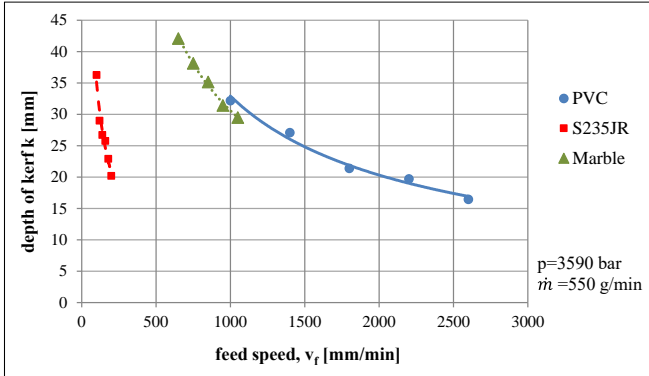


Figure 4 – Effect of feed rate on depth of kerf for different materials

Based on Figure 4, it can be concluded that of the three materials, structural steel is the most difficult to cut and polymer is the easiest. Polymer can be cut at about ten times and marble five times the speed of steel. This can be explained by the appearance of different erosion mechanisms in addition to physical mechanical properties.

However, the combined effect of the technological parameters cannot be read from Figures 3 and 4. The combined effect of the parameters was examined using the input energy. As described in chapter 2, we determined the theoretical input energy for each technological experiment and examined the change in the depth of kerf as a function of this. The change in the depth of kerf as a function of the input energy is shown in Figures 5. and 6. for marble and PVC materials.

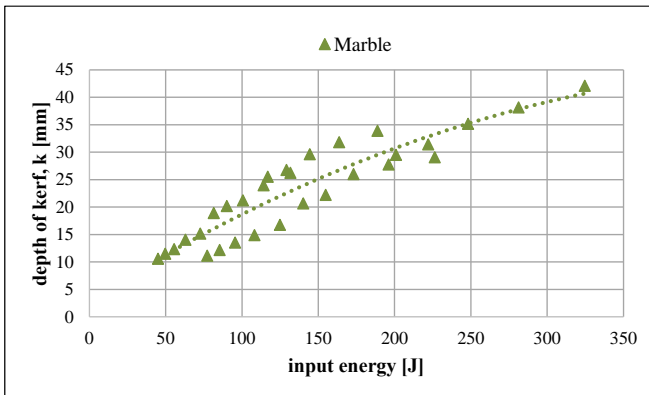


Figure 5 – Variation of the depth of kerf as a function of the input energy on white marble material

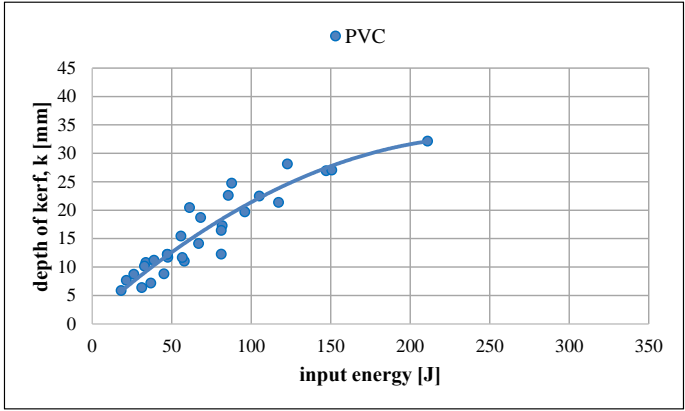


Figure 6 – Variation of the depth of kerf as a function of the input energy on PVC material

It can be seen from Figures 5 and 6 that the energy input clearly increases the depth of kerf, i.e. the efficiency of the cut. The change is not linear, for larger depths, the application of higher energy increases the efficiency of cutting less.

Comparing the Figures 5 and 6 also shows that the machinability of marble and PVC materials is very similar, both can be cut with a low energy input.

Figure 7 shows the change in the depth of kerf of all three materials as a function of the energy input.

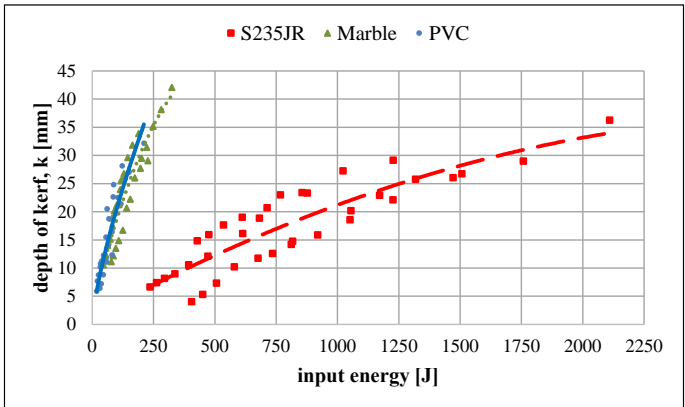


Figure 7 – Variation of cutting depth as a function of energy input on marble, PVC and structural steel materials

Based on Figure 7 it can be said that cutting S235JR structural steel requires the highest energy input of the three materials. The energy required can be up to ten times greater than when cutting PVC or marble. Increasing the energy increases the cutting efficiency for all the three materials.

5. Conclusions

Based on the evaluation of the experimental results, the following conclusions can be drawn regarding the kerf tests of the three types of machined materials:

- Increasing the feed speed reduces the depth of kerf, i.e. the efficiency of the cut, while increasing the pressure and abrasive flow increases it.
- Comparing the machining of different materials, it can be concluded that cutting steel is the least efficient and cutting PVC is the most productive.
- When using low feed speeds, marble - despite its relatively higher hardness - can be cut with a productivity similar to PVC. This can be explained by the so-called brittle erosion that occurs in marble.
- By examining the combined effect of the technological parameters using the theoretical energy input, it can be stated that the depth of kerf clearly increases with increasing cutting energy. This increase is not linear; the slope of the change is smaller for higher energy inputs.
- Cutting structural steel is much more difficult than cutting marble or PVC, requiring up to ten times more energy.

The results obtained show that in abrasive waterjet cutting, the cutting efficiency can be changed by controlling the input energy, which allows us to choose the feed-pressure-abrasive flow combination that provides the energy required to reach a given depth, according to the possibilities. In other words, we can ensure the same cutting efficiency for a given task at different pressures, abrasive flows and feed speeds.

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ДОСЛІДЖЕННЯ ВЗАЄМОЗВ'ЯЗКУ ВХІДНОЇ ЕНЕРГІЇ ТА ЕФЕКТИВНОСТІ ОБРОБКИ ПРИ ГІДРОАБРАЗИВНОМУ РІЗАННІ

Анотація. *Абразивна водоструменна обробка — це широко використовувана технологія для різання металевих, керамічних та полімерних листів. Сьогодні стає все більш важливим, щоб застосовувати технологічні параметри були ефективними та економічними. Це вимагає правильного вибору найважливіших технологічних параметрів. У цій статті ми розповідаємо про дослідження, в яких сукупний вплив технологічних параметрів, тобто взаємозв'язок між вхідною енергією та ефективністю, розглядався при обробці трьох матеріалів (метал, кераміка, полімер). На основі оцінки експериментальних результатів були зроблені деякі висновки. Збільшення швидкості подачі зменшує глибину прорізу, тобто ефективність розрізу, а збільшення тиску та абразивного потоку збільшує його. Порівнюючи обробку різних матеріалів, можна зробити висновок, що різання сталі є найменш ефективним, а різання ПВХ — найпродуктивнішим. При низьких швидкостях подачі мрамур — незважаючи на відносно вищу твердість — можна різати з продуктивністю, подібною до ПВХ. Це можна пояснити так званою крихкою ерозією, що відбувається в мрамурі. Аналізуючи сумарний вплив технологічних параметрів за теоретичними енергетичними вхідними даними, можна стверджувати, що глибина прориву явно зростає зі збільшенням енергії різання. Це збільшення не є лінійним; Нахил зміни менший для вищих енергетичних витрат. Різати конструкційну сталь набагато складніше, ніж різати мрамур або ПВХ, і це вимагає до десяти разів більше енергії. Отримані результати показують, що при абразивному водоструменному різанні ефективність різання можна змінити, контролюючи вхідну енергію, що дозволяє обрати комбінацію подачі-тиску-абразивного потоку, яка забезпечує енергію, необхідну для досягнення заданої глибини відповідно до можливостей.*

Ключові слова: *абразивна водоструменна обробка; технологічні параметри; енергія різання; вхідна енергія.*