

Optimization of the Cutting Process of Wood-Based Agglomerated Materials by Abrasive Water-Jet

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Abstract – The paper deals with the cutting MDF, OSB, and plywood boards by abrasive water-jet (GMA Garnet Australian, grain size 80, MESH = 0.188 mm), with a kerf width depending on the material properties and technical parameters (material thickness, cutting direction, abrasive flow, and feed speed). The entry of water-jet cutting in the longitudinal direction produces changes in the material due to lateral leads spreading the width of the cut joints by an average of 0.20 mm for MDF boards, 0.3 mm for OSB boards, and 0.17 mm for plywood. On the exit side of the material, the water has the opposite effect. In relation to the thickness of the material, the width of the cut joints increases. The experiment has shown that the optimum value of the feed speed is explicitly $400 \text{ mm}\cdot\text{min}^{-1}$, at which the kerf width reaches the lowest dimensions both at entry and exit, and the abrasive flow of $450 \text{ g}\cdot\text{min}^{-1}$ has been shown as optimum.

feed speed / water-jet / abrasive flow / kerf width / OSB / MDF / plywood

Kivonat – A faalapú agglomerált anyagok folyadéksugaras vágásának optimalizálása. E tanulmány az MDF, OSB és rétegelt lemezek abrazív szemcsés folyadéksugaras vágásának problémájával foglalkozik (GMA Garnet Australian, 80-as szemcseméret, 0,188 mm szitaméret), az anyagtulajdonságoktól és műszaki paraméterektől (anyagvastagság, vágási irány, szemcsekoncentráció és előtolási sebesség) függő vágásrés mérettel. A folyadéksugár longitudinális irányú belépése változásokat okoz az anyagban, mivel ez oldalirányban jobban szétteríti a vágásrés szélességét, MDF esetében átlag 0,20 mm-rel, OSB-nél átlag 0,30 mm-rel, rétegelt lemeznél pedig átlag 0,17 mm-rel. Az anyag kilépési oldalán a víz ezzel ellentétes hatást fejt ki. A vágásrés szélessége az anyagvastagsággal növekszik. A kísérletek megmutatták, hogy kimondottan a $400 \text{ mm}/\text{min}$ előtolás az optimális, melynél a vágásrés szélessége a legkisebb a bemeneti és a kimeneti oldalon egyaránt. Szemcsekoncentráció tekintetében $450 \text{ g}/\text{min}$ bizonyult optimálisnak.

előtolási sebesség / folyadéksugár / szemcsekoncentráció / vágásrés szélesség / OSB / MDF / rétegelt lemez

1 INTRODUCTION

With the application of the most-used natural resources, water and stone, we can cut almost every material. This makes the method of water-jet cutting (WJC) very efficient. It is a very simple, clean, and reliable technology, and therefore it becomes an alternative to other

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methods. But there are also limitations to WJC which should be monitored and improved as a technological process.

Since the first industrial application of cutting materials by abrasive water-jet (AWJ) has happened in a relatively short time, the number of applications has increased considerably and certainly made a significant impact in almost all industries. Use of high-pressure water-jet technology is no longer considered as "additional technology" in classical mechanical tillage. For the efficient, environmentally friendly, and fast processing of different types of (hard-machinable) materials, appropriate technology is needed. The machining of special materials is preferably made by unconventional technologies, which operate on different principles from traditional methods. Non-conventional technologies used for material removal are mainly electro-thermal, electrochemical, chemical, and mechanical. The highest commercial success from technologies based on the mechanical principle comes from a quantum energy/pressure water beam (Barcík et al. 2011a).

We can simply describe water-jet cutting (WJC) technology as a process of reducing material by mechanical impact of a liquid on manufactured material. The technology of applied WJC can be divided into two basic groups: cutting by clean, native water-jet and cutting by abrasive water-jet. In wood-processing practice, cutting by clean, native water-jet is known as chipless cutting and abrasive water-jet cutting as chip producing cutting (Engelmann et al. 2007). The technological process uses a high-pressure and narrow, high-speed stream of water (water pressure around 400 MPa) as a cutting tool (Beer 2007, Maňková 2000). The abrasive water-jet is a wedge tool with an undefined cutting edge (as used in grinding), and the decisive mechanism for removal of machined material is similar to the above-mentioned method. Cutting-wedges are formed with abrasive grains randomly oriented in the beam (Barcík 2007, Matúška 2003). Most equipment for WJC around the world achieves high pressures by using a multiplier. The principle of high pressure generation by the multiplier lies in the combination of two tightly linked pistons (Gerencsér – Bejő 2007, Hashish 1991, Fabian – Hloch 2005).

The focus of this work is optimization of the cutting process, which is carried out by abrasive water-jet, through selected agglomerated materials. This investigation includes the dependence of the kerf width (top kerf width and bottom kerf width) on material properties and also on technical parameters (material thickness, cutting direction, abrasive flow, and feed speed).

2 MATERIALS AND METHODS

2.1 Material preparation

Agglomerated materials used for this experiment were produced by Kronospan Jihlava, Czech Republic. Specific agglomerated materials that have been used for this experiment are: MDF boards, OSB boards, and plywood boards.

Selected agglomerated boards were cut to samples with the following specifications:

- thickness of the test sample:
 - 22 mm / 44 mm / 66 mm — MDF board
 - 16 mm / 32 mm / 48 mm — OSB
 - 18 mm / 36 mm / 54 mm — plywood
- required width of the test sample: $b = 180 \text{ mm} (\pm 2.5 \text{ mm})$
- required length of the test sample: $l = 500 \text{ mm} (\pm 5 \text{ mm})$
- the moisture content of the test samples: $w = 8\% (\pm 2\%)$.

Test samples were cut according to a basic cutting plan for sample preparation (Figure 1). Consequently, three cuts were made for each thickness on the samples to eliminate the effect of specific properties of the given sample (Figure 2).

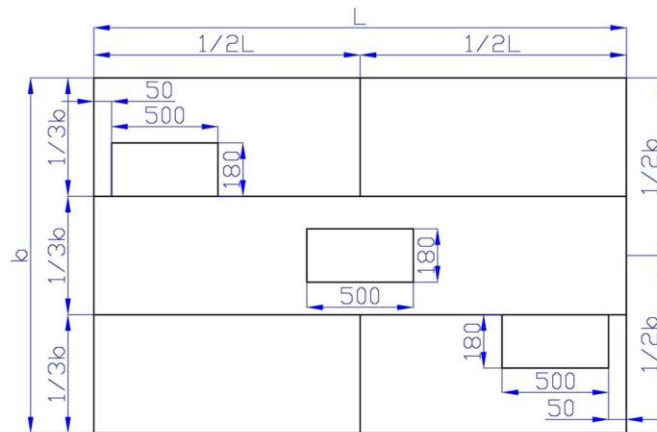


Figure 1. Preparation of test samples

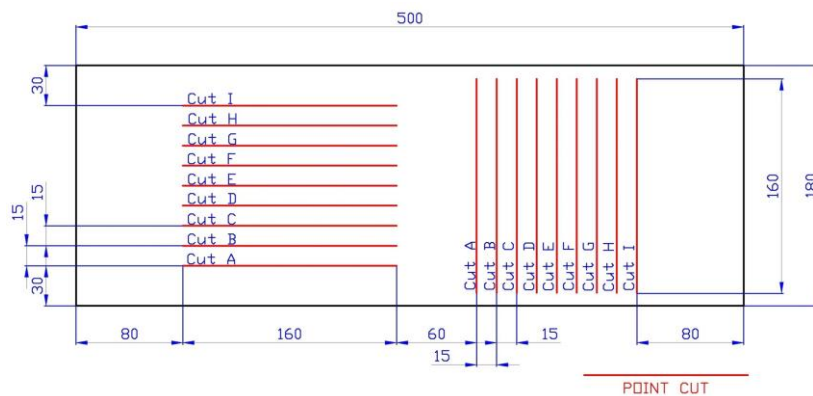


Figure 2. The cutting plan of the samples

2.2 Water-jet equipment

The methods corresponded to experimental tests presented by Barčík et al. (2009, 2011b) and Kviatková (2011). Cutting of samples was done by DEMA Ltd. in Zvolen. The equipment was assembled on the base of components from FLOW (USA) by PTV Ltd. (Prague) (Figure 3). It consisted of a high-pressure pump, PTV 37-60 Compact, and a work table with a water-jet head WJ 20 30 D-1Z supplied by PTV.

The technical parameters of the devices were similar to the research of Barčík et al. (2010a). The experiments were performed with the following technical parameters for the equipment:

- cutting liquid pressure: $4000 \text{ bar} = 400 \text{ MPa}$
- abrasive: Australian garnet GMA (grain size 80, MESH = 0.188 mm)
- diameter of abrasive jet nozzle: 1 mm
- diameter of water-jet: 0.013 inch = 0.33 mm
- distance of nozzle above the work piece: 4 mm
- abrasive mass flow: $m_a = 250 \text{ g}\cdot\text{min}^{-1}$, $m_a = 350 \text{ g}\cdot\text{min}^{-1}$, $m_a = 450 \text{ g}\cdot\text{min}^{-1}$
- feed speed: $v_f = 600 \text{ mm}\cdot\text{min}^{-1}$, $v_f = 400 \text{ mm}\cdot\text{min}^{-1}$, $v_f = 200 \text{ mm}\cdot\text{min}^{-1}$
- water consumption: $3.8 \text{ l}\cdot\text{min}^{-1}$
- water beam power output: 5kW

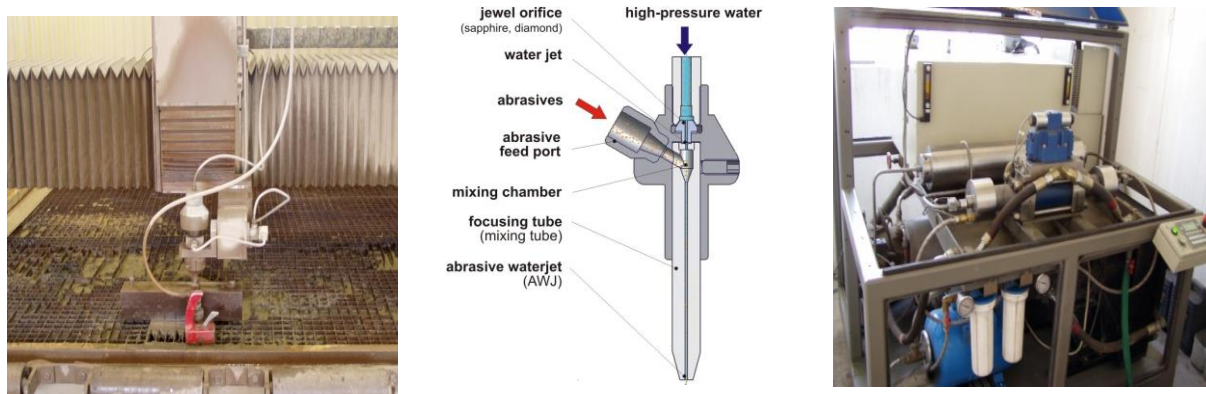


Figure 3. Equipment for cutting by water-jet (left), water-jet nozzle (center) and the high-pressure pump (multiplier) (right)

2.3 Measurement

This experiment was aimed at investigation of the kerf width, specifically top kerf width and bottom kerf width, which are represented in *Figure 4*.

- k_t – kerf width on the entry side (top kerf width): this kerf width, created by the passing of the abrasive water-jet through the material, was measured on the side where the water-jet goes into the material.
- k_b – kerf width on the exit side (bottom kerf width): this kerf width, created by the passing of the abrasive water-jet through the material, was measured on the side where the water-jet comes out of material.

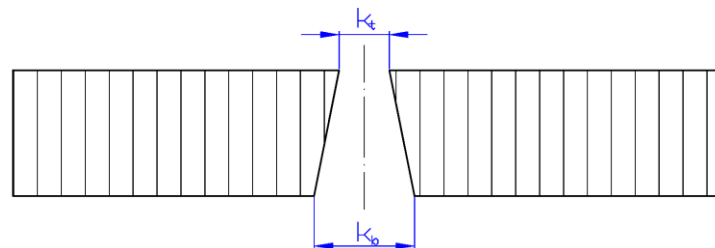


Figure 4. Illustration of the measured kerf widths (k_t – top kerf width, k_b – bottom kerf width)

1. Creation of digital photography

The creation of digital photography, with the kerf width and reference scale, is illustrated in *Figure 5* and *Figure 6*:

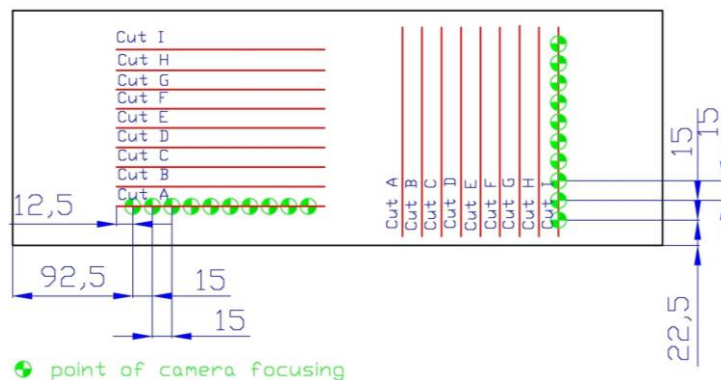


Figure 5. Measuring points of the kerf width

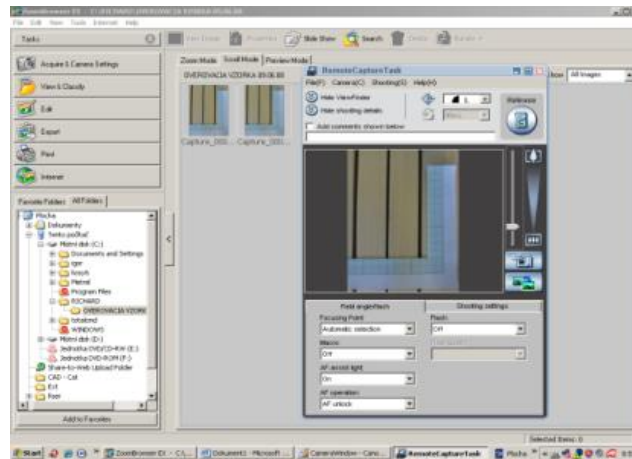


Figure 6. The example of digital picture creation with kerf for verification sample using the Zoom Browser EX 5.0 software

2. Measuring of kerf width

Measuring the kerf width on the exit of the water-jet process from the material becomes harder due to the rippled surface of cutting edge (Figure 9). For practical use the maximum size of the kerf is important (from the viewpoint of determining the material allowance for possible further work). The kerf width was measured as the distance of the two most remote parallel tangents placed to the cutting edge, while the evaluated cutting-edge length was always 15 mm.

3. Conversion of relative dimensions

The conversion of relative dimensions was done according to Equation 1:

$$k_b = \frac{k_p * a}{a_p} \quad (1)$$

where k_b is the actual width of the kerf [mm], k_p is the relative width of the kerf (the dimension measured by AutoCAD software from the digital picture), a is the actual dimension of the reference scale unit [mm], and a_p is the relative dimension of the reference scale unit (the dimension measured in AutoCAD software from the digital picture) (Figure 7).

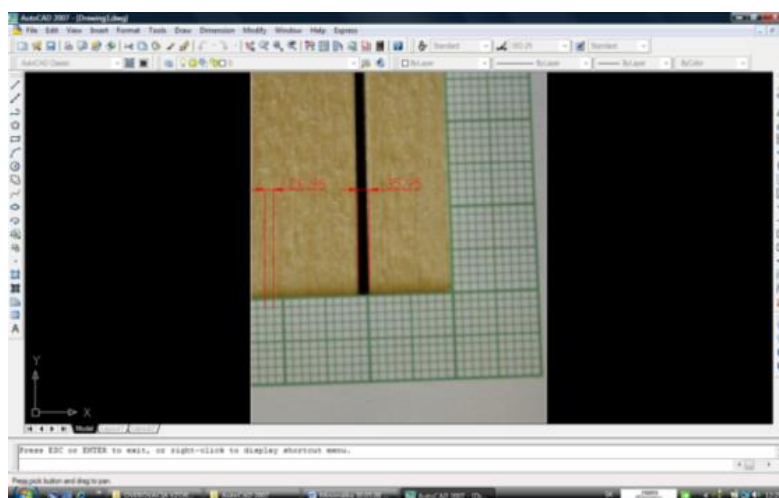


Figure 7. View of the AutoCAD software window during the relative measuring of dimensions

4. Statistical evaluation

From the given procedure we obtained a file of kerf width entry and exit values for all samples. Further, these values were evaluated with STATISTICA 7 software.

The devices and equipment for the measurement and evaluation were the following:

- personal computer (*COMPAQ EVO N 1020v*),
- digital camera (Canon Power Shot A520) (*Figure 8*),
- associated processing software for the digital camera (Canon-Zoom Browser EX 5.0) and for the comparative measuring of dimensions (AutoCAD 2007),
- reference scale (Barčík et al. 2010b)



Figure 8. Apparatus for measuring the kerf width

3 RESULTS AND DISCUSSION

3.1 MDF Boards

On the basis of multi-factorial variance analysis, the following sequence of significance of examined factors affecting the kerf width was found. The values are presented in *Table 1* and *Table 2*.

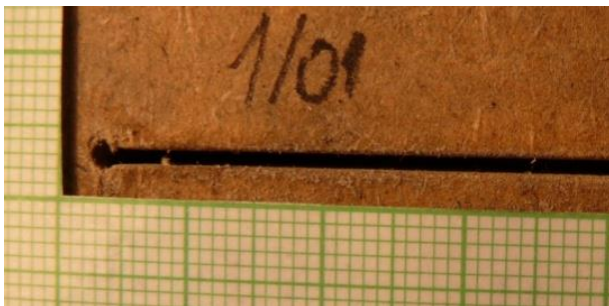


Figure 9. Digital picture of kerf on the MDF verification sample, kerf on the entry side of the material (left) and kerf on the exit side of the material (right)

Significance of entry factors:

1. cutting direction
2. feed speed
3. abrasive flow
4. thickness

Significance of exit factors:

1. thickness
2. feed speed
3. abrasive flow
4. cutting direction

Table 1. Values of multifactor analysis (MANOVA) at entry

Investigated factors	Sum of squares	Degrees of freedom	Scattering	F-test	Level of significance
	734.66	1.00	734.66	35,417.40	0.000
thickness	2.58	2.00	1.29	623.00	0.000
cutting direction	1.58	1.00	1.58	762.70	0.000
feed speed	1.20	2.00	0.60	289.40	0.000
abrasive flow	0.09	2.00	0.04	21.40	0.000
random factors	1.01	486.00	0.00		

Table 2. Values of multifactor analysis (MANOVA) at exit

Investigated factors	Sum of squares	Degrees of freedom	Scattering	F-test	Level of significance
	1,142.04	1.00	1,142.04	10,803.40	0.000
thickness	190.72	2.00	95.36	902.09	0.000
cutting direction	0.27	1.00	0.27	2.54	0.111
feed speed	58.54	2.00	29.27	276.86	0.000
abrasive flow	3.92	2.00	1.96	18.52	0.000
random factors	51.38	486.00	0.11		

Results of the effect of **cutting direction** on the kerf width are presented in *Figure 10*, *Table 3* and *Table 4*.

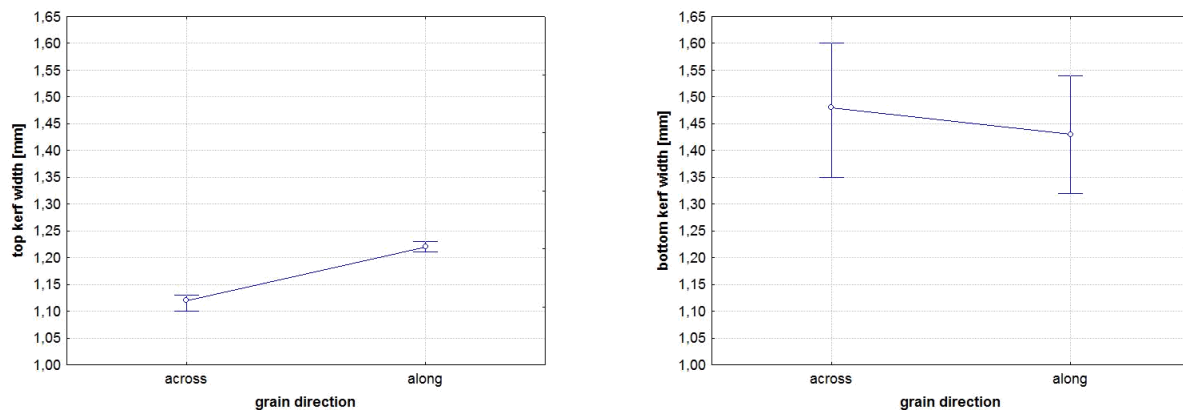


Figure 10. Graph of the kerf width dependence on the cutting direction of the worked material at entry (left) and at exit (right)

Table 3. Values of kerf-width dependence on cutting direction, at entry

Sample number	Cutting direction	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	across	1.12	0.01	1.10	1.13	270	100
2	along	1.22	0.01	1.21	1.23	270	107.0

Table 4. Values of kerf-width dependence on cutting direction, at exit

Sample number	Cutting direction	Arithmetic mean	Standard deviation	Minimum value	Maximum value	Number of measurements	%
				(mm)	(mm)		
1	across	1.48	0.06	1.35	1.60	270	100
2	along	1.43	0.06	1.32	1.54	270	98.01

During the cutting of samples across the basic technology flow we can see that the values of kerf width at entry are 0.10 mm lower compared with longitudinal cutting. The values of the kerf width at the exit of the water-jet from the work piece reach higher values with cross cutting by 0.05 mm than with longitudinal cutting. At the entry of the water-jet into the material, the kerf width was wider than in longitudinal cutting. These results can be explained by the fact that wood and agglomerated materials in this direction are more resistant to penetration by the water-jet. The time the abrasive particles act on the material is prolonged and due to this fact leads to a side effect of the washing-out of the kerf. This resistance depends not only on the mutual connection of the fibers, but also on the strength of the elements themselves, first of all from libriform fibers, whose strength is influenced by the S₂ layer of the secondary wall. The strength and stability also can vary with the shape and slenderness of the fibers. From the viewpoint of uniformity of kerf width, the dimensions of kerf proved more stable on both sides with the cutting along the grain compared with basic technology flow.

Results of the effect of **material thickness** on the kerf width are presented in Figure 11, Table 5 and Table 6.

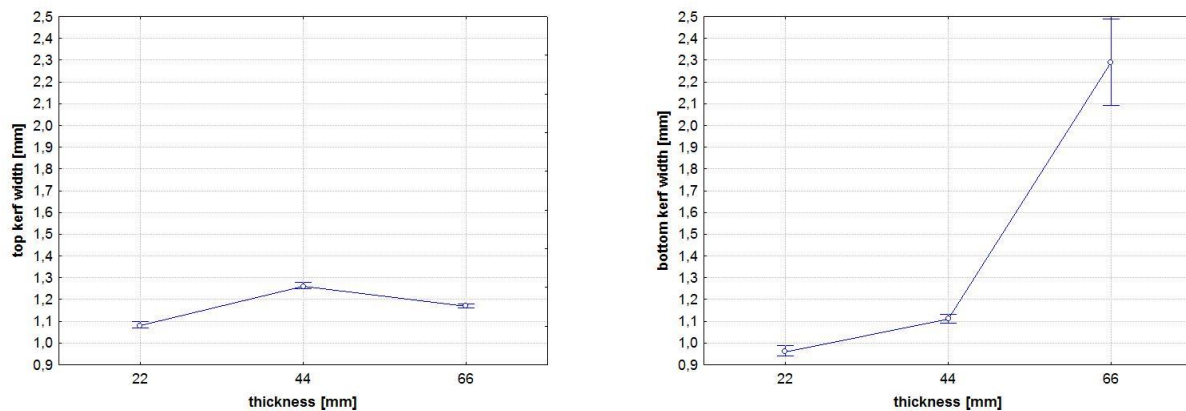


Figure 11. Graph of the kerf-width dependence on thickness of worked material at entry (left) and at exit (right)

Table 5. Values of kerf-width dependence on thickness, at entry

Sample number	Thickness	Arithmetic mean	Standard deviation	Minimum value	Maximum value	Number of measurements	%
				(mm)	(mm)		
1	22	1.08	0.01	1.07	1.10	180	100
2	44	1.26	0.01	1.25	1.28	180	128.28
3	66	1.17	0.01	1.16	1.18	180	117.51

Table 6. Values of kerf-width dependence on thickness, at exit

Sample number	Thickness	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	22	0.96	0.01	0.94	0.99	180	100
2	44	1.11	0.01	1.09	1.13	180	108.24
3	66	2.29	0.10	2.09	2.49	180	144.33

A 0.18 mm increase in kerf width at entry was reached by the change in thickness of material from 22 mm to 44 mm. A 0.9 mm decrease in kerf width was caused by the change of material thickness from 44 mm to 66 mm.

A change in sample thickness from 22 mm to 44 mm caused a 0.15 mm increase in kerf width at the exit and a change in thickness from 44 mm to 66 mm caused increased kerf width of 1.18 mm. The greater the thickness the higher the amount of abrasive particles gathered in the cut, and these particles apart from the primary effect, severing of material, also cause the side effect of widening of the kerf due to the washing-out of material. The increased values of the kerf width in the test samples of higher thickness were significantly influenced by the lag of the water-jet caused by the gradual loss of its kinetic energy.

From this experiment we can see that the optimum material thickness is 22 mm. This thickness caused the lowest kerf-width values in the entry and also in the exit.

Results of the **feed speed** influence:

At entry, the change of the feed speed from $200 \text{ mm}\cdot\text{min}^{-1}$ to $400 \text{ mm}\cdot\text{min}^{-1}$ caused 3 mm lower values in kerf width. The change of feed speed from $400 \text{ mm}\cdot\text{min}^{-1}$ to $600 \text{ mm}\cdot\text{min}^{-1}$ caused an increase in kerf width of 5 mm.

At exit, the change in feed speed from $200 \text{ mm}\cdot\text{min}^{-1}$ to $400 \text{ mm}\cdot\text{min}^{-1}$ caused an increase of kerf width of 6 mm. The change of feed speed from $400 \text{ mm}\cdot\text{min}^{-1}$ to $600 \text{ mm}\cdot\text{min}^{-1}$ caused an increase of 3 mm.

The experiment has shown that the optimum value of the feed speed is explicitly $400 \text{ mm}\cdot\text{min}^{-1}$, at which the kerf width reaches the lowest dimensions both at entry and exit.

Results of **abrasive flow** influence on kerf width:

With the change of the added amount of abrasive from $250 \text{ g}\cdot\text{min}^{-1}$ to $350 \text{ g}\cdot\text{min}^{-1}$, the values of the kerf width increased at entry by 2 mm, and then with an increase of the abrasive amount to $450 \text{ g}\cdot\text{min}^{-1}$ they increased by another 2 mm.

By changing the added amount of abrasive from $250 \text{ g}\cdot\text{min}^{-1}$ to $350 \text{ g}\cdot\text{min}^{-1}$, in the exit of the water-jet process from the worked material, the kerf-width values decreased by 3 mm. With the change of the amount of abrasive from $350 \text{ g}\cdot\text{min}^{-1}$ to $450 \text{ g}\cdot\text{min}^{-1}$, the values decreased by 6 mm.

With an increase of the abrasive mass flow up to $450 \text{ g}\cdot\text{min}^{-1}$, the kinetic energy of the particles was consumed by their mutual contact, which created the secondary effect of washing-out of the material at entry and the subsequent narrowing of the kerf width at the exit due to energy loss. However, in comparison with the uniformity of the values at both sides, the value of $450 \text{ g}\cdot\text{min}^{-1}$ abrasive mass flow has seemed optimum.

3.2 OSB Boards

Cutting of OSB boards was represented by more ripped kerf at entry side in comparison with MDF boards (Figure 12). The individual values, for this type of material, are presented in Table 7 and Table 8.

On the basis of multifactorial variance analysis, the following sequence of significance of examined factors affecting the kerf width was found.

Significance of entry factors:

1. cutting direction
2. feed speed
3. abrasive flow
4. thickness

Significance of exit factors:

1. thickness
2. feed speed
3. abrasive flow
4. cutting direction

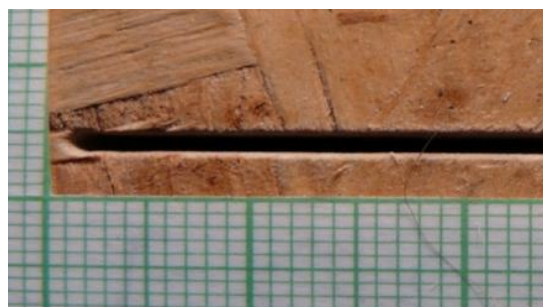
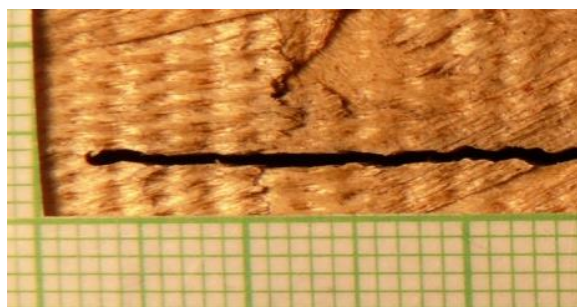


Figure 12. Digital picture of kerf on the OSB verification sample, kerf at the entry of the water-jet into the material (left) and kerf at the exit of the water-jet from the material (right)

Table 7. Values of multifactor analysis (MANOVA) at entry

Investigated factors	Sum of squares	Degrees of freedom	Scattering	F-test	Level of significance
	662.022	1	662.022	296,662.9	0.000
thickness	0.0358	2	0.0179	8.0	0.000
cutting direction	4.1639	1	4.1639	1,865.9	0.000
feed speed	1.4355	2	0.7177	321.6	0.000
abrasive flow	0.2071	2	0.1036	46.4	0.000
random factors	1.0845	486	0.0022		

Table 8. Values of multifactor analysis (MANOVA) at exit

Investigated factors	Sum of squares	Degrees of freedom	Scattering	F-test	Level of significance
	1,040.613	1	1,040.613	25,465.51	0.000
thickness	45.281	2	22.641	554.06	0.000
cutting direction	0.111	1	0.111	2.72	0.100
feed speed	5.681	2	2.841	69.52	0.000
abrasive flow	0.519	2	0.26	6.36	0.002
random factors	19.86	486	0.041		

Results of the effect of cutting direction on the kerf width are presented in Figure 13, Table 9, and Table 10.

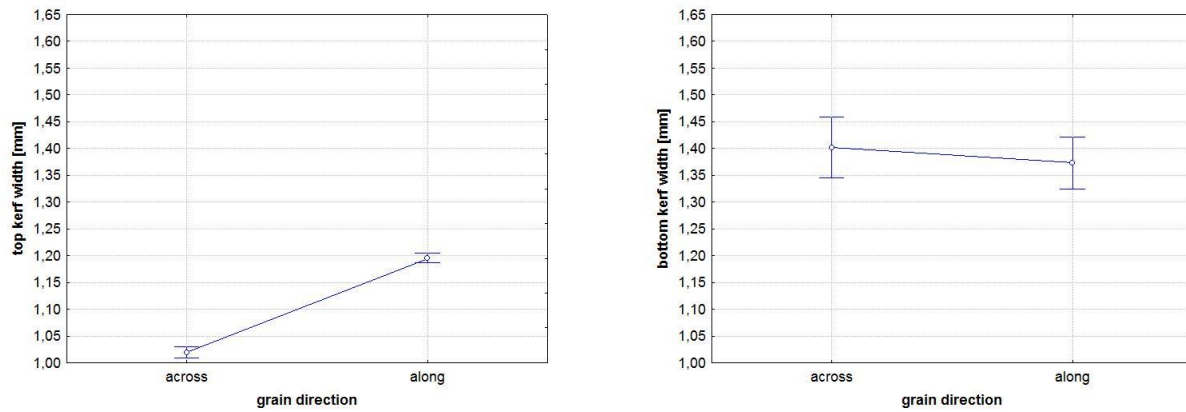


Figure 13. Graph of the kerf-width dependence on cutting direction of worked material, at entry (left) and exit (right)

During the cross cutting of samples according to material flow we can see that the values of kerf width at entry were 0.17 mm lower compared with longitudinal cutting. During the cross cutting of samples according to material flow we can see that values of kerf width at exit are 0.029 mm higher compared with longitudinal cutting.

Table 9. Values of kerf-width dependence on cutting direction, at entry

Sample number	Cutting direction	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	across	1.019	0.006	1.009	1.030	270	100
2	along	1.195	0.004	1.187	1.204	270	117.23

Table 10. Values of kerf-width dependence on cutting direction, at exit

Sample number	Cutting direction	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	across	1.403	0.029	1.346	1.459	270	100
2	along	1.374	0.025	1.325	1.423	270	97.96

Results of the **feed speed** influence:

At the entry of the water-jet, the change of the feed speed from 200 mm·min⁻¹ to 400 mm·min⁻¹ caused 7.1 mm lower values of kerf width. The change of feed speed to 600 mm·min⁻¹ caused lower kerf width by 9.67 mm. At the exit of the water-jet from the material, the change in feed speed from 200 mm·min⁻¹ to 400 mm·min⁻¹ caused decreased kerf width by 5.21 mm, and the increasing of feed speed to 600 mm·min⁻¹ caused an increase of 10.34 mm.

Influence of **abrasive flow** on kerf width:

With the change of the added amount of abrasive from 250 g·min⁻¹ to 350 g·min⁻¹, the values of the kerf width decreased at entry by 0.16 mm, and then with an increase of the abrasive amount to 450 g·min⁻¹ they increased by 3.71 mm. With the change of the added amount of abrasive from 250 g·min⁻¹ to 370 g·min⁻¹, the values of the kerf width decreased at

exit by 3.31 mm, and then with an increase of the abrasive amount to $450 \text{ g}\cdot\text{min}^{-1}$ they decreased by 5.26 mm.

Results of the influence of **material thickness** on kerf width are presented in *Figure 14*, *Table 11* and *Table 12*.

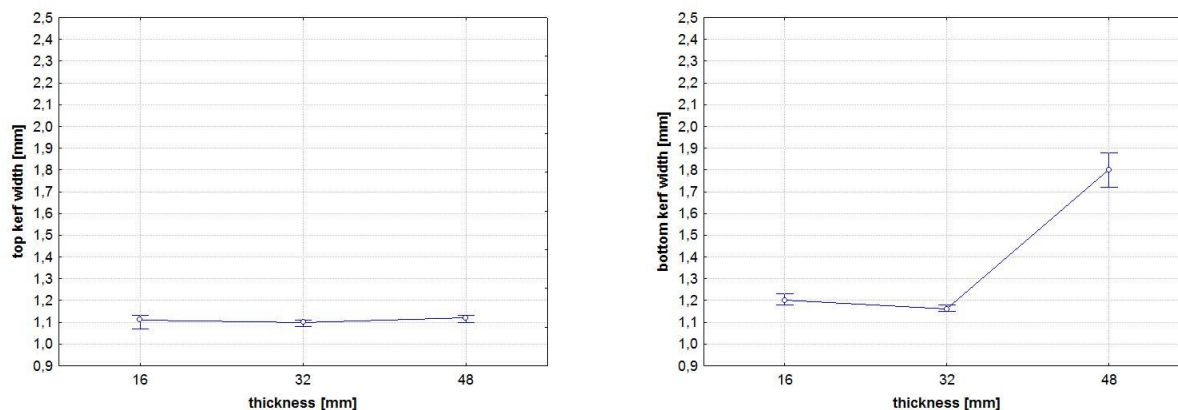


Figure 14. Graph of the kerf-width dependence on thickness of worked material, at entry (left) and exit (right)

The 0.01 mm decrease in kerf width at entry was reached by the change in thickness of material from 16 mm to 32 mm. The 0.02 mm increase in kerf width was caused by the change of material thickness from 32 mm to 48 mm. The 0.04 mm decrease of kerf width at exit was reached by the change in thickness of material from 16 mm to 32 mm. The 0.64 mm increase of kerf width was caused by the change of material thickness from 32 mm to 48 mm.

Table 11. Values of kerf-width dependence on thickness, at entry

Sample number	Thickness	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	16	1.11	0.01	1.07	1.13	180	100
2	32	1.10	0.01	1.08	1.11	180	98.74
3	48	1.12	0.01	1.10	1.13	180	101.34

Table 12. Values of kerf-width dependence on thickness, at exit

Sample number	Thickness	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	16	1.20	0.01	1.18	1.23	180	100
2	32	1.16	0.01	1.15	1.18	180	96.74
3	48	1.80	0.04	1.72	1.88	180	149.34

3.3 Plywood

Cutting of plywood was different in relation to kerf width because of wider entry kerf (*Figure 15*). The importance of monitored factors influencing kerf width on plywood is presented in *Table 13* and *Table 14*.

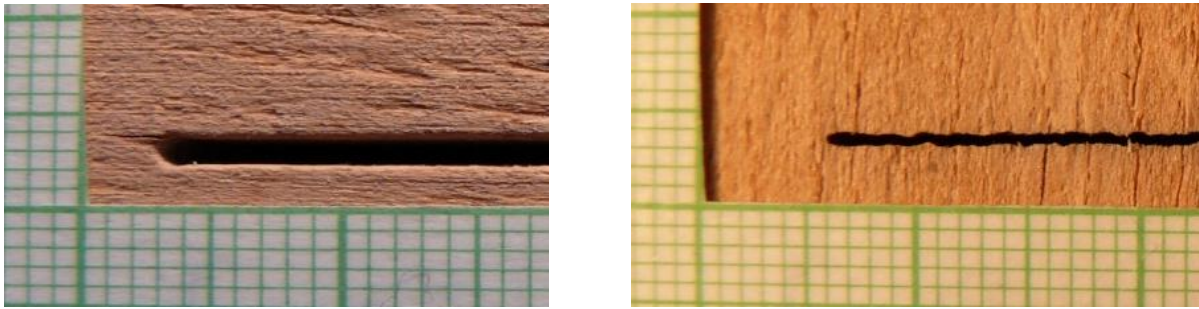


Figure 15. Digital picture of kerf on the plywood verification sample, kerf on the entry of the water-jet into material (left) and kerf on the exit of the water-jet from the material (right)

Table 13. Values of multifactor analysis (MANOVA) at entry

Investigated factors	Sum of squares	Degrees of freedom	Scattering	F-test	Level of significance
	729.335	1	729.3352	24,4285.6	0.000
thickness	0.8664	2	0.4332	145.1	0.000
cutting direction	8.8182	1	8.8182	2,953.6	0.000
feed speed	1.4337	2	0.7169	240.1	0.000
abrasive flow	0.2854	2	0.1427	47.8	0.000
random factors	1.451	486	0.003		

Table 14. Values of multifactor analysis (MANOVA) at exit

Investigated factors	Sum of squares	Degrees of freedom	Scattering	F-test	Level of significance
	768.0995	1	768.0995	5,2711.9	0.000
thickness	15.6655	2	7.8328	537.53	0.000
cutting direction	8.2088	1	8.2088	563.34	0.000
feed speed	1.528	2	0.764	52.43	0.000
abrasive flow	0.0381	2	0.0191	1.31	0.271
random factors	19.86	486	0.041		

Significance of entry factors:

1. cutting direction
2. feed speed
3. thickness
4. abrasive flow

Significance of exit factors:

1. cutting direction
2. thickness
3. feed speed
4. abrasive flow

The effect of cutting direction on kerf width is presented in Figure 16, Table 15 and Table 16.

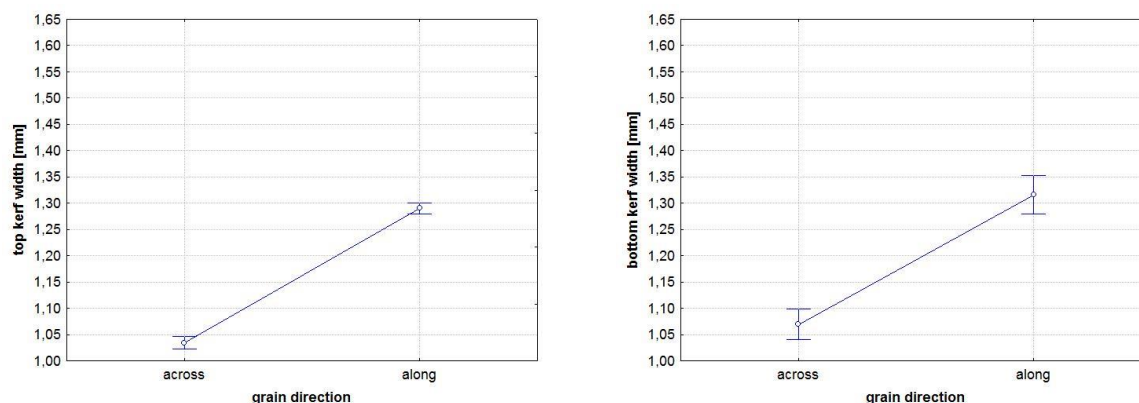


Figure 16. Graph of the kerf-width dependence on cutting direction of the worked material, at entry (left) and exit (right)

Table 15. Values of kerf-width dependence on cutting direction, at entry

Sample number	Cutting direction	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	across	1.034	0.006	1.022	1.047	270	100
2	along	1.290	0.006	1.279	1.301	270	124.7

Table 16 Values of kerf-width dependence on cutting direction, at exit

Sample number	Cutting direction	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	across	1.069	0.015	1.040	1.099	270	100
2	along	1.316	0.018	1.280	1.352	270	123.05

The values of kerf width at entry were about 0.256 mm lower compared with longitudinal cutting at cross cutting. Values of kerf width at exit are 0.249 mm lower compared with longitudinal cutting.

Results of the **feed speed** influence:

At the entry of the water-jet, the change of the feed speed from 200 mm·min⁻¹ to 400 mm·min⁻¹ caused 3.62 mm lower values of kerf width. The change of feed speed to 600 mm·min⁻¹ caused lower kerf width by 4.09 mm. At the exit of the water-jet from the material, the change in feed speed from 200 mm·min⁻¹ to 400 mm·min⁻¹ caused decreased kerf width by 4.2 mm, and the increasing of feed speed to 600 mm·min⁻¹ caused its decrease by 1.17 mm.

Results of the influence of thickness on kerf width are presented in Figure 17, Table 17 and Table 18.

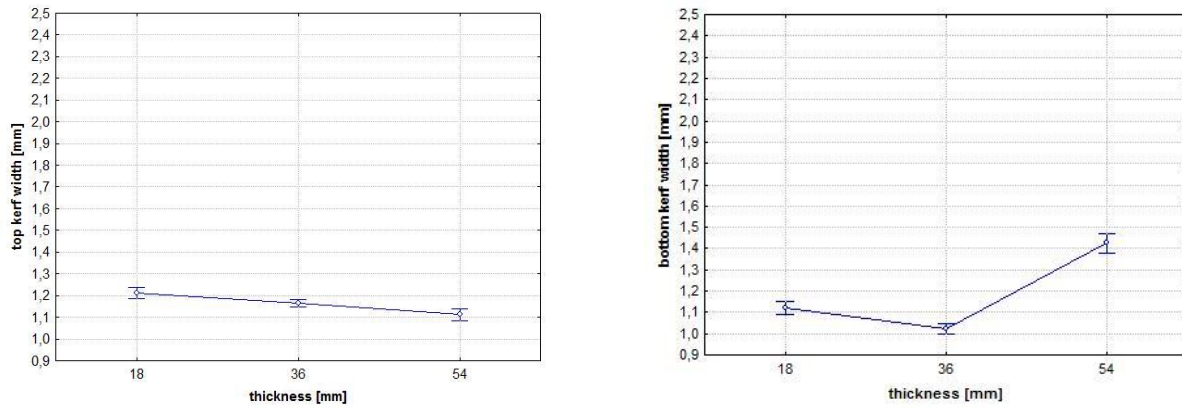


Figure 17. Graph of kerf-width dependence on thickness of worked material, at entry (left) and exit (right)

Table 17. Values of kerf-width dependence on thickness, at entry

Sample number	Thickness	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	18	1.21	0.1	1.19	1.24	180	100
2	36	1.17	0.1	1.15	1.18	180	97.25
3	54	1.12	0.1	1.09	1.14	180	92.14

Table 18. Values of kerf-width dependence on thickness, at exit

Sample number	Thickness	Arithmetic mean	Standard deviation	Minimum value (mm)	Maximum value (mm)	Number of measurements	%
1	18	1.12	0.1	1.09	1.15	180	100
2	36	1.03	0.1	1.05	1.00	180	94.59
3	54	1.43	0.1	1.38	1.47	180	132.54

Results of the influence of **thickness**:

A 0.04 mm decrease in kerf width at entry was caused by the change in thickness of material from 18 mm to 36 mm. A 0.05 mm increase in kerf width was caused by the change of material thickness from 36 mm to 54 mm. A 0.09 mm decrease in kerf width at exit was caused by the change in thickness of material from 18 mm to 36 mm. A 0.4 mm increase in kerf width was caused by the change of material thickness to (Figure 17).

Influence of **abrasive flow** on kerf width:

With the growth of the added amount of abrasive from $250 \text{ g}\cdot\text{min}^{-1}$ to $350 \text{ g}\cdot\text{min}^{-1}$, the values of kerf width increased at entry by 3.1 mm, and then with the change of the abrasive amount to $450 \text{ g}\cdot\text{min}^{-1}$, values increased by 4.9 mm. With the growth of the added amount of abrasive from $250 \text{ g}\cdot\text{min}^{-1}$ to $350 \text{ g}\cdot\text{min}^{-1}$, the values of kerf width increased at exit by 1.73 mm. Growth of the abrasive amount to $450 \text{ g}\cdot\text{min}^{-1}$ caused increased kerf width by 0.73 mm. See the presented graphical values for the most important factor and for all materials.

Water-jet cutting is an economical way to cut 2D shapes into a wide range of materials with no tooling costs. The unique process of water-jet cutting provides reasonably good edge quality, no burrs, and usually eliminates the need for secondary finishing processes. The

process also generates no heat so the material edge is unaffected and there is no distortion. Water-jet cutting can cut single or multi-layer materials (Rašner et al. 2001).

It is necessary to take an economic view of the whole process of WJC. It should be compared with other cutting techniques from the point of view of costs and benefits. It must be monitored and costs quantified for WJC assembly and the whole material flow, including fixed costs, variable costs (e.g., energy consumption), and also alternative costs related to other (conventional) methods of cutting. Another necessary parameter is time of production (cutting) which affects total capacity and also productivity of an assembly for the material flow. Last but not least, the economic viewpoint must also consider the amount of waste from the water-jet cutting compared with conventional methods of cutting (Rajnoha – Aláč 2003).

4 CONCLUSIONS

The experiments have shown that utilization of the water-jet for cutting agglomerated materials is a suitable method when it is used with the appropriate combination of technical and technological parameters. The most important benefit of this technology is small kerf width compared with other cutting technologies. From the viewpoint of kerf-width equality on both sides of the worked material, we can see more stable dimensions of kerf width with materials cut in the longitudinal direction. From the viewpoint of the technological parameters used, the feed speed of $400 \text{ mm} \cdot \text{min}^{-1}$ and the abrasive flow of $450 \text{ g} \cdot \text{min}^{-1}$ have been shown to be optimum. With thicknesses exceeding 44 mm, the method becomes less efficient and it's necessary the improvement of material by additional working.

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