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EFFECT OF THE CHOSEN PARAMETERS ON DEFLECTION ANGLE BETWEEN CUTTING SIDES DURING THE CUTTING OF AGLOMERATED MATERIALS BY WATER JET

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ABSTRACT

The paper deals with the cutting of agglomerated materials by abrasive water jet from the point of view of deflection angle between the cutting sides. It shows the results of deflection angle in dependance on technical and technological parameters (sliding speed and abrasive mass flow) and material parameters (material thickness and cutting direction). Paper also contains the methodology for assessment the effect of these parameters related to the basic cutting directions. Our paper presents significant results of experiments made by this methodology applied on MDF, OSB boards and on technical beech plywood.

KEYWORD: Shift speed, abrasive flow, abrasive water-jet, cutting by abrasive water-jet.

INTRODUCTION

Since the first industrial application of cutting materials by abrasive waterjet (AWJ) has passed a relatively short time, while the number of applications had increased considerably and certainly made a significant share in almost all industries. Use of high-pressure water jet technology is no longer considered as "additional technology" in the classic - mechanical tillage. For efficient, environmentally friendly and fast processing of different types (hard machinable) materials are needed appropriate technology. The machining of special materials is preferably made by unconventional technologies, which operate on different principles than traditional methods. Non-conventional technologies use for material removal mainly electrothermal,

electrochemical, chemical and mechanical principle. The highest commercial success from technologies based on mechanical principle has quantum energy-pressure water beam.

Elimination of particular deficiencies within the practical use of AWJ in wood industry is the goal of our paper which presents the results from experimental investigation of the influence of selected factors on the angular deflection dimension in cutting sides (β). Experimental monitoring of parameter β is in the context of the further possibility of using the excess for processing.

The principle of waterjet machining technology can be easily explained as removing material by mechanical impacted fluid on the workpiece (Bernd 1993).

Waterjet cutting technology is a unique, future-oriented option for the introduction of high automation for heavy duty cutting virtually all types of materials (Fabian and Hloch 2005).

There is used clean water after chemical and mechanical processing without added mechanical particles. There are fully used the properties of water at high pressures (water pressure around 400 MPa) as a cutting tool (Maňková 2000).

Nature of material breach by water jet based on the principle that the beam - tool moving at a rate (max. 885 ms^{-1} at a pressure of 400 MPa), can be seen in terms of its effect as a solid body. Disruption of material is the result of transformation the input energy of continuous drops flow - the beam into the material. Energy input causes tension in a very small area (e.g. 0.3 mm diameter beam represents an area of 0.07 mm^2), which leads to deformation of original structure and removing of a certain volume of material. Water jet with abrasive ranks among many wedge tools with undefined cutting edge (like grinding) and also the basic mechanism of material removing is similar to the above mentioned method. Cutting wedges are formed with abrasive grains randomly oriented in the beam (Barcík 2007).

MATERIAL AND METHODS

The chosen methodology of experiments corresponds to (Kvietková 2010).

During the experiment there were used samples of aglomerated materials where:

• thickness of the test sample:
  22 mm / 44 mm / 66 mm - MDF,
  16 mm / 32 mm / 48 mm - OSB,
  18 mm / 36 mm / 54 mm - plywood.
• the required width of the test sample: w = 180 mm (± 2.5 mm)
• required length of the test sample: l = 500 mm (± 5 mm)
• moisture content of the test samples: w = 8 % (± 2 %).

Cutting of samples was done in DEMA Ltd. Zvolen. The equipment is assembled on the base of components of American firm FLOW Int. by the firm PTV Ltd. Praha (Fig. 1). It consists of a high-pressure pump PTV 37-60 Compact, and a work table with water-jet head WJ 20 30 D-1Z supplied by the firm PTV.

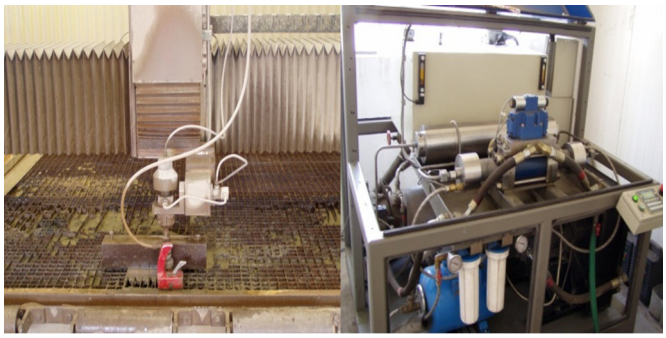
Working cuts were performed on three samples for each thickness in order to eliminate the impact of specific characteristics of the sample (Fig. 2).

Technical parameters of the devices are similar to (Barcík 2010).

The experiments were realized with technical parameters of the equipment:

- cutting liquid pressure: 4000 bar = 400 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 jet nozzle above the workpiece: 4 mm
- abrasive mass flow: m_a = 250 g.min^{-1}/m_a = 350 g. min^{-1}/m_a=450 g. min^{-1}
- feed rate: v_f = 600 mm.min^{-1}/v_f = 400 mm.min^{-1}/v_f = 200 mm.min^{-1}



a) b)

Fig. 1: Technological equipment for cutting by water-jet DEMA Ltd. a) work-table of the equipment b) high-pressure pump (multiplier).

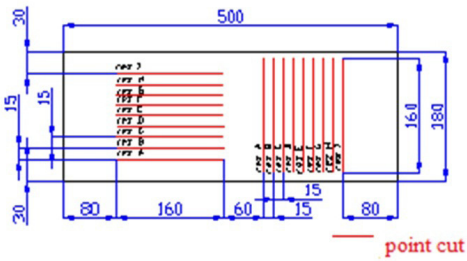


Fig. 2: Cutting plan of the test sample.

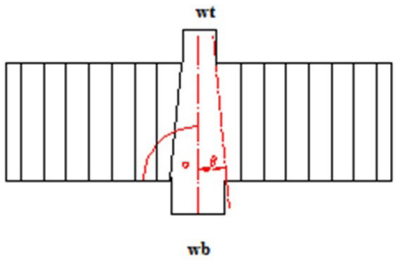


Fig. 3: Illustration of the deflection angle of the cutting sides (β).

Observed variable definition:

• β - the angle of deflection of the cutting sides (taper angle): it is the deflection angle between operated sufrace plane and a plane perpendicular to the ground plane of a material (Fig. 3).

Procedur of measuring

Before an evaluation of the deflection angle of the cutting sides an evaluation of the cutting kerf was made. If a kert width is known on input and output and if we do not consider asymmetry of the cutting gap the deflection angle can be presented as the following formula:

$$tg\beta = \frac{\frac{1}{2}(w_b - w_t)}{h}$$

where: β – deflection angle of the cutting sides (°)
w_t - kerf width at the input of water jet into the material (mm),
w_b - kerf width at the output of water jet from the material (mm),
h - depth of a cut (mm).

RESULTS AND DISCUSSION

By the evaluation of measured data from 160 combinations according to formula we have obtained basic file of values. On the base of multifactor variance analysis, in the following tables and charts there are presented data of significance for monitored factors. The values of deflection angle varied from 0.000005 to 0.002153.

MDF board

Results of monitored factors impacted deflection angle within MDF boards are presented in Tabs. 1, 2, 3, 4, 5 and Figs. 4, 5, 6, 7.

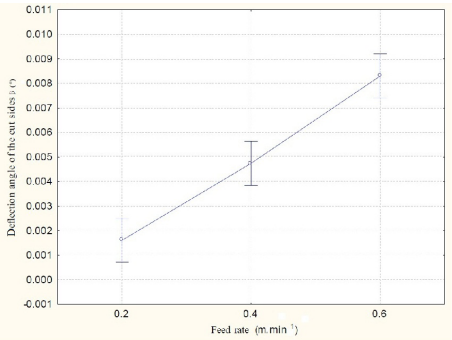


Fig. 4: Effect of shift speed on the deflection angle for MDF board.

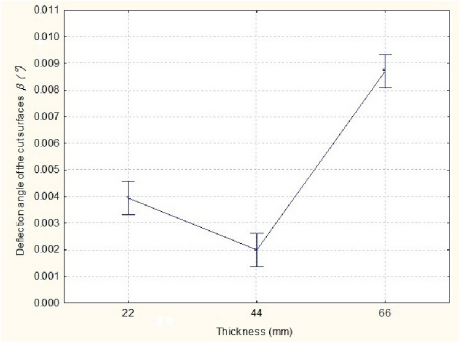


Fig. 5: Effect of material thickness on the deflection angle of the MDF cutting sides.

Tab. 1: Values of factor analysis (MANOVA) for MDF board.

Deflection angle of the cut sides	Sum of squares	Degrees of freedom	Variance	F test	p –Significance level
Intercept	0.012881	1	0.012881	723.58	0.000000
(1) Thickness	0.004306	2	0.002153	120.94	0.000000
(2) Cutting direction	0.000005	1	0.000005	0.2800	0.596939
(3) Feed rate	0.004027	2	0.002014	113.11	0.000000
(4) Abrasive flow	0.000062	2	0.000031	1.7523	0.174461
Thickness * Cutting direction	0.000255	2	0.000127	7.1565	0.000865
Thickness * Feed rate	0.004867	4	0.001217	68.351	0.000000
Thickness * Abrasive flow	0.000051	4	0.000013	0.7179	0.579943
Cutting direction * Abrasive flow	0.000005	2	0.000003	0.1406	0.868845
Feed rate * Abrasive flow	0.000631	4	0.000158	8.8564	0.000001
Thickness * Feed rate * Abrasive flow	0.001343	8	0.000168	9.4310	0.000000

Tab. 2: Deflection angle of the cutting sides related to shift speed for MDF board.

Sample number	Feed rate (m.min^{-1})	Average deflection angle of cut surfaces β (°)
1	200	0.001611
2	400	0.004746
3	600	0.008296

Justification comes from the results of kerf widthat the input and output of AWJ, it means that through the kerf come more abrasive particles and it results into higher energy potential of AWJ. More particles in the space cause less water jet lag and there is also no additional expansion of kerf width. So, this impacts extension of deflection angle between cutting sides.

Tab. 3: The angle of deflection of the cutting sides in the current thickness of MDF board.

Sample number	Feed rate (m.min^{-1})	Average deflection angle of cut surfaces β (°)
1	22	0.003939
2	44	0.001997
3	66	0.008717

Results obtained from the measurement say that the greater thickness of the sample significantly impacts the water jet lag, its gradual loss of kinetic energy, what results into the deflection angle of cutting sides. Significant effect has also so called disintegration of water jet for different wood materials, which is caused by different sizes of resistance against cutting (the larger resistance is, the longer transition of AWJ through the material). This causes greater extension of kerf width at the output of AWJ from the material, compared to AWJ input into the material and thereby increasing of the deflection.

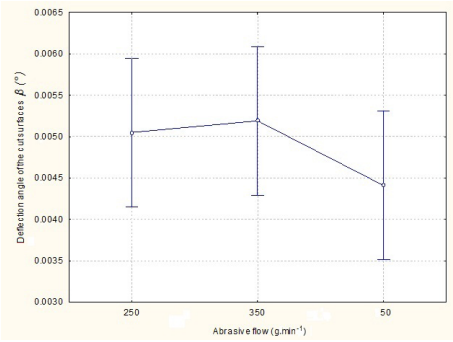


Fig. 6: Effect of abrasive flow on the deflection angle of the MDF cutting sides.

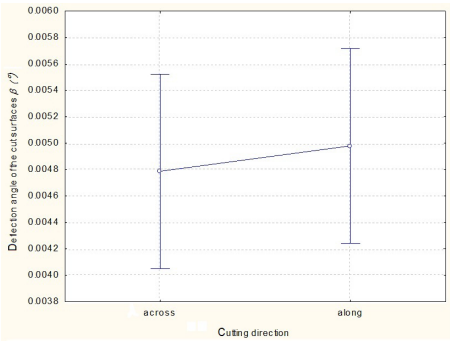


Fig. 7: Effect of cutting direction on the deflection angle of the MDF cutting sides.

Tab. 4: Deflection angle of the cutting sides with respect to abrasive flow for MDF board.

Sample number	Feed rate ($m.min^{-1}$)	Average deflection angle of cut surfaces β (°)
1	250	0.002145
2	350	0.001787
3	450	0.001963

Impact of abrasive flow was statistically unimportant related to deflection angle of cutting sides during the evaluation of agglomerated material - MDF boards, see (Fig. 6) and (Tab. 4), where it is evident that the monitored factor has minimal impact on deflection angle.

Tab. 5: The angle of deflection with respect to the cutting direction of MDF board.

Sample number	Cutting direction	Average deflection angle of cut surfaces β (°)
1	across	0.004788
2	along	0.004987

During the cutting of MDF boards is the influence of cutting direction on deflection angle second statistically unimportant factor. We can see, as it is given in Fig. 7, that monitored factor minimally impacts deflection angle of the cutting sides.

OSB board

Impacts of shift speed, material thickness, the direction of cutting and abrasive mass flow on the β the β during the OSB cutting is presented in Tabs. 6, 7, 8, 9, 10 and in Figs. 8, 9, 10, 11.

Tab. 6: Values of factor analysis (MANOVA) for OSB boards.

Deflection angle of the cut sides	Sum of squares	Degrees of freedom	Variance	F test	p –Significance level
Intercept	0.012172	1	0.012172	1268.557	0.000000
(1) Thickness	0.002081	2	0.001041	108.458	0.000000
(2) Cutting direction	0.000331	1	0.000331	34.496	0.000000
(3) Feed rate	0.000887	2	0.000443	46.220	0.000000
(4) Abrasive flow	0.000000	2	0.000000	0.011	0.989390
Thickness * Feed rate	0.001736	4	0.000434	45.225	0.000000
Cutting direction * Abrasive flow	0.000186	2	0.000093	9.681	0.000075
Feed rate *Thickness	0.000213	4	0.000053	5.538	0.000229
Thickness * Cutting direction * Feed rate	0.000284	4	0.000071	7.395	0.000009
Thickness * Feed rate * Abrasive flow	0.000526	8	0.000066	6.857	0.000000
Cutting direction * Feed rate * Abrasive flow	0.000148	4	0.000037	3.869	0.004180

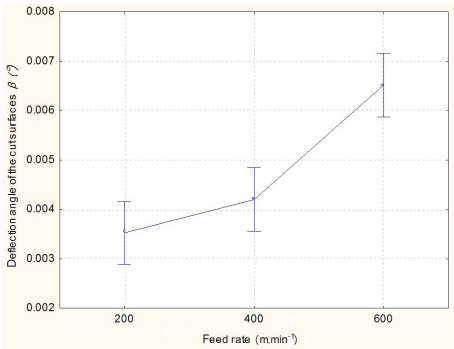


Fig. 8: Effect of shift speed on the deflection angle for OSB board.

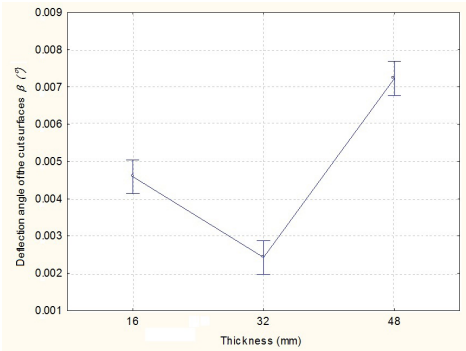


Fig. 9: Effect of material thickness on the deflection angle for OSB board.

Tab. 7: Deflection angle of the cutting sides with respect to shift speed for OSB board.

Sample number	Feed rate (m.min^{-1})	Average deflection angle of cut surfaces β (°)
1	200	0.003526
2	400	0.004199
3	600	0.006518

Increasing shift speed causes increasing in deflection angle as i tis presented in Fig. 8 and in Tab. 7. When changing the shift speed from 200 to 400 m.min^{-1}, the deflection angle of the cutting sides has increased by 0.0006° (given indicator refers to Tab. 7) and during the change of shift speed from 400 to 600 m.min^{-1}, the value of deflection angle has increased by 0.0024° (given indicator refers to Tab. 7).

Tab. 8: Deflection angle of the cutting sides with respect to the material thickness for OSB board.

Sample number	Thickness (mm)	Average deflection angle of cut surfaces β (°)
1	16	0.004591
2	32	0.002425
3	48	0.007227

Deflection angle in MDF and also in OSB boards is affected by the disintegration of water jet. This is evident for various wood materials and it is given by the different material resistance against cutting.

Increasing the deflection angle of the cutting sides in the longitudinal direction of cutting can be explained by the orientation of wood elements contained in the OSB material within its structure.

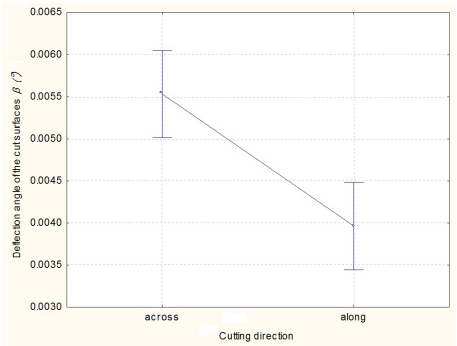


Fig. 10: Effect of cutting direction on the deflection angle for OSB board.

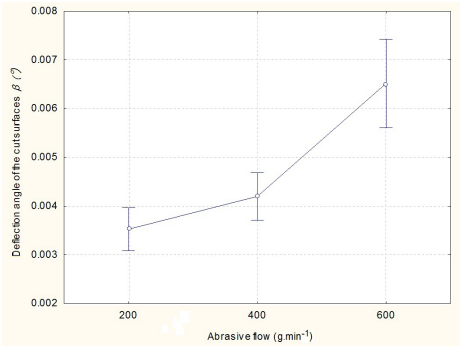


Fig. 11: Effect of abrasive flow onthe deflection angle of the cutting sides for OSB board.

Tab. 9: Deflection angle of the cutting sides with respect to the direction of cutting the OSB board.

Sample number	Cutting direction	Average deflection angle of cut surfaces β (°)
1	across	0.004788
2	along	0.004987

Tab. 10: Deflection angle of the cutting sides with respect to abrasive flow for OSB board.

Sample number	Abrasive flow ($g.min^{-1}$)	Average deflection angle of cut surfaces β (°)
1	250	0.003626
2	350	0.004199
3	450	0.006518

As it is evident in MDF also in OSB boards the effect of abrasive flow is statistically unimportant.

Technical beech plywood

Results of monitored material and technical factors impacted deflection angle β for the industrial plywoods are presented in Tabs. 11, 12, 13, 14, 15 and in Figs. 12, 13, 14, 15.

We can see from the results that higher shift speed causes increasing of the deflection angle between cutting sides.

Results of deflection angle in relation with material thickness can be explained as it was for MDF boards.

When taking into account kerf width, the reached results show that extension of kerf width at the input of AWJ into material, while changing the direction of cutting, is caused by the orientation of particular wood elements which are part of wood structure. When cutting along with fibres, cell elements are oriented according to their length dimension they are identical with the direction of the tool shift and separation is mainly in the intercellular space.

Tab. 11: Values from the factor analysis (MANOVA) for plywood.

Deflection angle of the cut sides	Sum of squares	Degrees of freedom	Variance	F test	p –Significance level
Intercept	0.012172	1	0.012172	1268.557	0.000000
(1) Thickness	0.002081	2	0.001041	108.458	0.000000
(2) Cutting direction	0.000331	1	0.000331	34.496	0.000000
(3) Feed rate	0.000887	2	0.000443	46.220	0.000000
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Thickness * Feed rate * Abrasive flow	0.000526	8	0.000066	6.857	0.000000
Cutting direction * Feed rate * Abrasive flow	0.000148	4	0.000037	3.869	0.004180

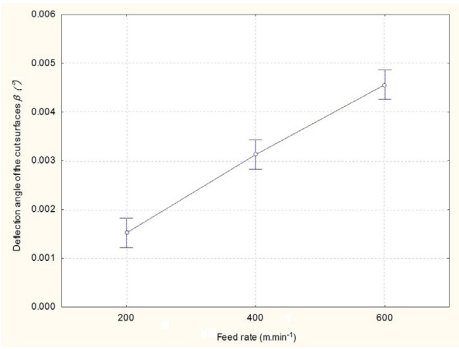

Fig. 12: Effect of shift speed on the deflection angle of the plywood cutting sides.

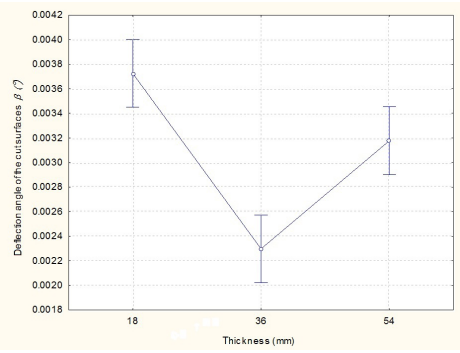

Fig. 13: Effect of material thickness on the deflection angle for the plywood.

Tab. 12: Deflection angle of the cutting sides with respect to shift speed for plywood.

Sample number	Feed rate (m.min^{-1})	Average deflection angle of cut surfaces β (°)
1	200	0.001515
2	400	0.003421
3	600	0.004561

Tab. 13: Deflection angle of the cutting sides with respect to material thickness of plywood.

Sample number	Thickness (mm)	average deflection angle of cut surfaces β (°)
1	18	0.003726
2	36	0.002297
3	54	0.003177

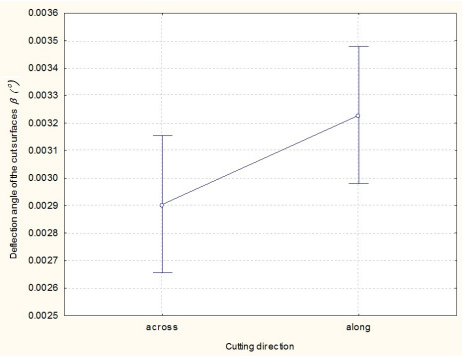

Fig. 14: Effect of cutting direction on the deflection angle for plywood.

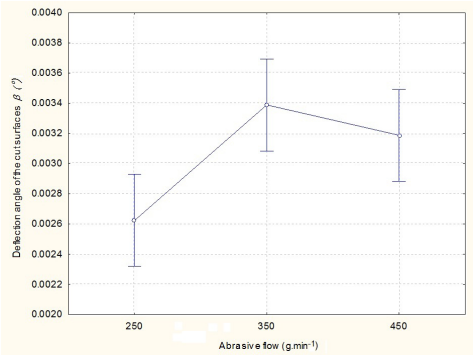

Fig. 15: Effect of abrasive flow on the deflection angle for plywood.

Tab. 14: Deflection angle with respect to the cutting direction for plywood.

Sample number	Cutting direction	Average deflection angle of cut surfaces β (°)
1	across	0.002905
2	along	0.003229

During the cross cutting of boards the separation of particles is mainly across the cellular elements. Reducing energy of abrasive water jet it increases the risk of snapping cell element from the structure of a material. This event has an influence on the deflection angle increasing within the longitudinal cutting, taking into account the structure of particular wood materials.

Tab. 15: Deflection angle of the cut ting sides with respect to abrasive flow for plywood.

Sample number	Abrasive flow ($g.min^{-1}$)	Average deflection angle of cut surfaces β (°)
1	250	0.002623
2	350	0.003389
3	450	0.003188

Deflection angle of the cutting sides increased by 0.007° (given indicator refers to Tab. 15) when the abrasive flow had changed from 250 $g.min^{-1}$ to 350 $g.min^{-1}$. Another increasing of abrasive flow caused angle growth by 0.005° (given indicator refers to Tab. 15), taking into account basic value of abrasive flow at amount 250 $g.min^{-1}$. So we can say more abrasive particles come through energy of these particles is further used in the cutting process. Its growth in given area leads to decreasing of water jet lag and but there is no further enlargement of the kerf width.

Economic viewpoint

In the first, it must be taken into account decision whether to use water jet cutting (WJC) or conventional cutting methods. Waterjet cutting is an economical way to cut 2D shapes in a very wide range of materials with no tooling costs. The unique process of waterjet 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. Waterjet cutting can be used for cutting single or multi-layer materials.

It is very necessary to take into account economic viewpoint of the whole WJC process. It should be compared WJC to other cutting techniques from the point of view of costs and benefits. It must be monitored and quantified costs on WJC assembly and on the whole material flow. It means fixed costs on the machinery, and then variable costs on energy and material consumption and also alternative costs related to other (conventional) methods of cutting. Very necessary parameters which should be considered are also costs on potential repairs or on bad quality performance of water jet cutting (Rajnoha 2003).

Necesary economic aspect is also total time of production (cutting, former and following necessary operations) what affects total capacity utilization and also productivity of an assembly within the material flow. The shorter time of processing leads to more satisfied customer. Of course, production must correlate with demand and it must meet quality demands (Rašner 2001).

Last but not least, economic viewpoint must consider also amount of waste from the water jet cutting compared to conventional methods of cutting.

CONCLUSION

Water jet technology is considered as spectral technology with many applications and modifications, so utilization the term „water-jet machining“ - WJM is highly appropriate. Extended application scale is given by the versatility of this technology especially with environmental impact. Deflection angle of cutting sides is a parameter directly dependent on the kerf width.

The issue, which this paper shows is far more complex did not deal with any author (Kminiak 2010), therefore the obtained results can not be exactly comparable with other authors. With bibliographic work captures mainly the results of cutting non-wood materials (e.g. metals, plastics, stone...).

All experiments confirmed that shift speed is very important parameter. Increasing the shift speed causes growth of the deflection angle. Effect of abrasive flow is not very important parameter for MDF and OSB boards and it has only minimal impact on the deflection angle. But on the other hand, abrasive flow is very significant parameter on the deflection angle for plywood and it increases this angle. Increasing the thickness of material also causes growth of the deflection angle. The direction of cutting has only minimal impact on the deflection angle for MDF boards. Deflection angle for OSB boards and for technical beech plywood is impacted by elements which are contained in the wood material within its structure.

The whole process of cutting wood based materials by AWJ must be considered from the

complex point of view because every material has its specifications and therefore particular parameters must be optimized with dependance on these specific features of materials. We can see from the evaluation of results that during the monitoring of parameters impact on β angle, it is not necessary to take into account extra-measure for the final processing.

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