WOOD RESEARCH
59 (3): 2014
499-508

FABRICATION OF STRUCTURAL JOINERY ITEMS OF SOLID WOOD BY THE MEAN OF ABRASIVE WATER JET METHOD

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(Received April 2014)

ABSTRACT

The article deals with the issues related to the potential use of the abrasive water jet method for solid wood cutting at the fabrication of structural joinery items as far as the resulting cut quality concerns.

The resulting cut quality evaluation is based on two key indices: Kerf width and finished surface irregularities. The article covers the whole range of wood species (coniferous, broadleaf circular-porous and broadleaf scattered-porous wood species), typically used cutting patterns (crosswise to the fibers, alongside the fibers tangentially and alongside the fibers radially) and thicknesses of timber used typically in the building and cabinetmaking industries (up to 75 mm). The abrasive water jet method is evaluated within the maximum usable cutting liquid pressure of 400 MPa and at standard range of the feed speed (from 0.2 to 0.6 $m \cdot s^{-1}$) and the abrasive agent mass flow rate (from 250 to 450 $g \cdot min^{-1}$).

The article defines clearly the usability of the method as far as the cut material thickness concerns. It quantifies the impact of the individual factors generating the standard patterns of the solid wood cutting on the quality indices. At the same time, is shows the possibilities of the cut quality homogenization by the change of the cutting pattern, using mathematic definition of the process factors on the resulting cut quality.

KEYWORDS: Abrasive water jet, resulting cut quality, cutting pattern, feed speed, abrasive agent mass flow rate.

INTRODUCTION

The designers of the structural joinery items are favoring the use of complicated shapes in their designs. However, their fabrication requires the application of specific methods for the material machining. Prokeš (1982) and Maňková (2000) specify four possible basic material machining methods: Saw cutting with linear reverse travel (scroll-saw based), CNC milling, laser cutting and abrasive water jet cutting.

Fig. 1: AWJ use alternatives for the structural joinery items fabrication: a) wooden floors, b) walls facing and c) stairway handrails.

Each of the mentioned methods has its both advantages and disadvantages. As the main disadvantage of the abrasive water jet has been considered the incompatibility of water with wood. However, as shown in the works of Gerencsér and Bejóm (2003) and Barcík and Kvietková (2011), this doubt is not reasonable since when cutting the solid wood with abrasive water jet, the moisture is penetrating only to the surface layers of the wood. And 24 hours after the cutting, the moisture fraction is between 0 and 3 % higher than before the cutting. Therefore, the moisture increase is relatively nonsignificant and does not constitute serious obstacle from the practical point of view.

Once this basic doubt had been settled, another doubts related to the cut quality arose. We understand as the cutting method quality the result of the entire tool action affecting the product overall quality, which is conditioned by three types of accuracy: Shape, dimensional and surface (roughness) (Lisičan et al. 1996, STN EN ISO 4287 1997).

In comparison with the traditional methods with solid tool, the situation for the abrasive water jet becomes more complicated since the tool consists of liquid jet containing the abrasive agent. The material removal within the zone corresponds to the removal at the mechanical grinding method of the material machining. The removal extent and intensity depend mainly on the ratio of the mechanical properties of the machined material and the cutting material (the abrasive agent) (Beer 2007, Engemann 1993). Taking this point of view in account, the abrasive water jet can be included among the polygonal tools without defined cutting edge (Barcík et al. 2011, Havlík 1995). The resulting machined surface consists of cutting areas created by cutting wedges (abrasive agent grains) (Krajný 1998, Matuška 2003). The quality of surface machined by AWJ is typically worsening in the direction from the input point to the material towards the output point. Like all high-energy jet methods, also AWJ leaves visible striation on the machined surface (Hashis 1991, Kulekci 2002). Such striation affects adversely the machined surfaces quality as well as the shape accuracy of the products. The striation starts only at certain depth under the surface and deepens gradually. Thus, the machined surface consists of flat zone and rough striated zone. This is caused by the gradual loss of the AWJ kinetic energy and its deviation during the material penetration. This generates two typical zones, which change the surface texture. The relatively flat zone in the upper part of the cut results from the cutting wear and the other, striated zone in the lower part results as the aftermath of the deformation wear during the AWJ cutting (Krajný 1998, Havlík 1995).

According to the definition of Požgaj et al. (1997) or Prokeš (1982), the wood is 3-D-wise anisotropic material. This makes the wood machining significantly more complicated than other materials. The quality of its machined surface depends not only on the processed wood species (since each wood specie has different anatomic structure), but also on the machining direction of the given surface (radial, tangential or transversal) due to the variable orientation of the wood elements in the individual directions (Dzurenda 2008, Siklienka and Očkajová 2003).

At the combination of the abrasive water jet as the tool and wood as the specific material, the doubt on reduced quality shows up as reasonable. In their papers, Gerencsér and Bejóm (2003) and Matuška (2003) concluded that the kerf width on both AWJ input and output points becomes a significant index of the AWJ cut quality, affecting the dimensional accuracy; the same shall apply for the machined surface irregularities.

The goal hereof is the plotting of the potential to achieve the required cut quality by the mean of AWJ cut, with regard to the wood species range (coniferous, broadleaf circular-porous and broadleaf scattered-porous wood species), typically used cutting patterns (crosswise to the fibers, alongside the fibers tangentially and alongside the fibers radially) and thickness range of timber used typically in the building and cabinetmaking industries (up to 75 mm).

MATERIAL AND METHODS

Both radial and tangential test pieces of species of English oak (*Quercus robur*), European beech (*Fagus sylvatica*) and European spruce (*Picea abies*), 25, 50 and 75 mm thick, with moisture of w = 8 % (±2 %) were chosen for the experiment.

The test pieces were cut on an experimental equipment delivered by DEMA spol. s.r.o. Zvolen and consisting of PTV 37 - 60 Compact high-pressure pump and work bench with WJ 20 30 D -1Z cutting head. The experiment took place at the cutting liquid pressure of 400 MPa, with Australian grenade GMA (grain size: 80 MESH). The variable parameters of the experiment were the abrasive agent mass flow rate at three levels: ma = 250, ma =350 and ma = 450 g·min^{-1} and the feed speed, also at three levels: vf = 0.6, vf = 0.4 and vf = 0.2 m·min^{-1}.

Ten cuts 200 mm long were made for each combination of the following parameters: wood species – timber type – cutting pattern (alongside/transversally to the fibers) – timber thickness – abrasive agent mass flow rate – feed speed.

Measurements of the kerf width and the resulting surface quality were carried out on the created cuts. The methodology is taken into account by the applicable law for the wooden products quality evaluation.

For the kerf width measurement, the cut was divided in sections of 15 mm each. There, the kerf width was measured as the distance between two parallel tangents of the cutting edge. The kerf width was evaluated on the AWJ input side to the material marked as wt, and on the AWJ output side from the material as wb. Photographic method was used for the kerf width measurements.

The finished surface irregularity was evaluated by the mean of arithmetical mean deviation of the roughness profile Ra (which is defined in the currently applicable STN EN ISO 4287 2009 as mean arithmetical value of the profile absolute deviations within the basic length measured on the roughness profile derived from the primary profile by suppressing the items with great wavelengths). The measurement of the arithmetical mean deviation of the roughness profile was carried out on the LPM 120 laser 2-D profile meter working on triangulation basis. The measurement was carried out in three trails parallel with the sample loading area: The first one, 5 mm from the AWJ input side to the material, the second one in the cutting height center, and the third one 5 mm from the AWJ output side from the material. The evaluated length was 10 cm.

RESULTS AND DISCUSSION

In order to create an objective view on the possibilities of the AWJ use for the fabrication of structural joinery items, the article introduced the both indices – kerf width and finished surface irregularity – as well as their development within all the 324 combinations of the variable parameters. The results are shown in form of conclusions based on statistical evaluation of the obtained data using the statistics software while keeping the significance level of 95 %.

The basic knowledge for the AWJ application on solid wood cutting is that no cutting of material 75 mm thick is possible at the given cutting parameters as for this thickness, the material cut is not complete.

Kerf width

We may conclude that the effect of all examined factors is statistically significant.

The kerf width on the AWJ input side to the material is influenced by the monitored factors in the following order of importance: Feed speed, cut height, timber type, wood species, abrasive agent mass flow rate and cutting direction. The kerf width average values on the AWJ input side to the material are ranged between 1.03 and 1.25 mm. Tab. 1 shows the average kerf widths on the AWJ input side to the material.

For the kerf width in the AWJ output side to the material, the given order did not apply. It changed as follows: cut height, wood species, cutting direction, feed speed, timber type and abrasive agent mass flow rate. The kerf width average values on the AWJ output side from the material are ranged between 0.86 and 2.76 mm. Tab. 1 shows the average kerf widths on the AWJ output side from the material.

Tab. 1: Average kerf widths on the AWJ input and output sides for various wood species and sample thicknesses.

Wood species	Cut height (mm)	Kerf width of input side (mm)			Wood species	Cut height (mm)	Kerf width of output side (mm)		
		average	-95.00 %	+95.00 %			average	-95.00 %	+95.00 %
Spruce	25	1.05	1.03	1.06	**Spruce**	25	0.94	0.89	1.00
Spruce	50	1.10	1.09	1.11	**Spruce**	50	1.40	1.35	1.46
Oak	25	1.14	1.13	1.15	**Oak**	25	1.00	0.94	1.05
Oak	50	1.08	1.06	1.09	**Oak**	50	2.71	2.65	2.76
Beech	25	1.08	1.07	1.09	**Beech**	25	0.92	0.86	0.97
Beech	50	1.24	1.23	1.25	**Beech**	50	2.06	2.00	2.12

The most important factor affecting the kerf width is the feed speed. The obtained data have proven that the feed speed increase will cause the kerf width reduction of the AWJ input side to the material, and, on the contrary, the kerf width increase on the AWJ output side from the material. The following linear equations may describe this relation:

- for the AWJ input side to the material: $w_t = -0{,}275\,v_f + 1{,}2233\,(R^2 = 0{,}9973)$
- for the AWJ output side from the material: $w_b = v_f + 1{,}1067\,(R^2 = 0{,}9992)$

With the cutting height increase, the kerf width on either AWJ side of the material is increasing. The cutting height change from 25 to 50 mm means an average increase of the kerf width on the AWJ input side to the material by 0.05 mm and on the AWJ output side from the material by 1.1 mm.

Different kerf widths can be observed also for different timber types. Based on the statistical evaluation we may conclude that at identical process parameters, greater kerf width can be achieved for radial timber than for tangential timber. This shall apply for the both AWJ sides of the material. The average difference on the AWJ input side to the material is 0.05 mm and on the output side 0.12 mm.

Each of the examined wood species has different internal structure and physical and mechanical properties. Therefore, the AWJ interaction of these wood species is not identical. This is manifested on the kerf width. The kerf width differences for AWJ input and output of the material increase in the order spruce – beech – oak, as shown also in the Tab. 1 and Fig. 2.

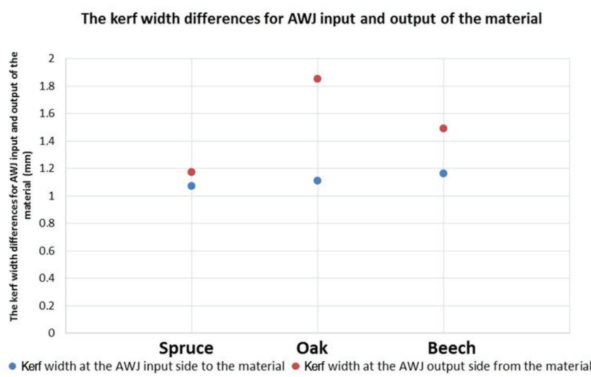

Fig. 2: The kerf width differences for AWJ input and output of the material increase in the order spruce – beech – oak.

Both abrasive agent mass flow rate and feed speed belong among the process parameters. For the both, different effect on the kerf width can be observed for AWJ input and output sides of the material. While on the AWJ input side to the material the kerf width increases with the abrasive agent mass flow rate, on the AWJ output side from the material, the kerf width decreases. Like for the feed speed, this relation can be described by the mean of linear equations:

- for the AWJ input side to the material: $w_t = 0.0003\,m_a + 1.0258\,(R^2 = 0.9868)$
- for the AWJ output side from the material: $w_b = -0.0008\,m_a + 1.7658\,(R^2 = 0.9985)$

Due to the fibers cutting direction change from the longitudinal to the transversal, on the AWJ input side to the material, the kerf width decreases in average by 0.24 mm. Due to the fibers cutting direction change from the longitudinal to the transversal, on the AWJ output side from the material, the kerf width increases in average by 0.36 mm.

Finished surface irregularity

The finished surface irregularity has been evaluated on the basis of the index of arithmetical mean deviation of the roughness profile Ra. Except the timber type and abrasive agent mass flow rate, the impact of all examined factors is statistically significant. According to their statistical significance, the examined factors were set in the following order: measurement trail, cutting direction, cut height, wood species, feed speed, abrasive agent mass flow rate (statistically nonsignificant) and timber type (statistically nonsignificant). The measured values of the arithmetical mean deviations of the roughness profile ranged from 8 to 37 µm.

See the Tab. 2 for the effect of the measurement trail position on the finished surface irregularity.

Tab. 2: Effect of the measurement trail position on the finished surface irregularity.

Measurement trail	Arithmetic mean deviation of roughness profile Ra			
	Average value (µm)	Standard error (µm)	-95.00 % (µm)	+95.00 % (µm)
A	12.728	1.052	10.657	14.798
B	14.420	1.052	12.350	16.491
C	27.421	1.052	25.351	29.491

As proven by the statistical evaluation of the obtained data, no statistically significant difference exists between trail A and trail B. However, within trail C, the difference is statistically significant and it represents a 90- % increase in comparison with the trails A and B. Since for the final product, only the maximum value of the surface arithmetical mean deviation is significant, we will reduce the results introduction for the given trail only.

The following applies for the cutting direction effect: the values of the surface arithmetic mean deviation Ra are greater when cutting the fibers transversally than longitudinally. The difference of the average value of the arithmetic mean deviation of the surface roughness profile between transversal and longitudinal directions is as high as 21 µm.

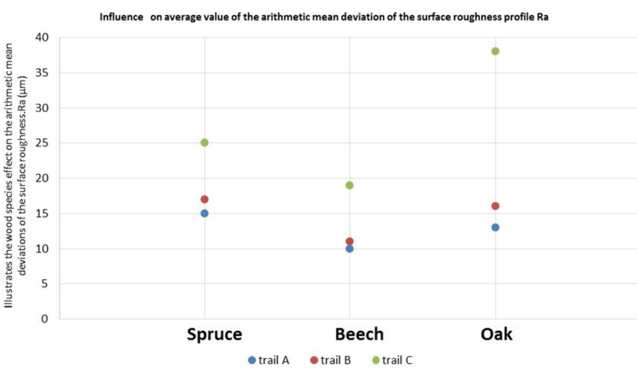

Fig. 3: Wood species effect on the arithmetic mean deviations of the surface roughness.

The effect of the cut height (sample thickness) is statistically nonsignificant for the trails A and B. It shows up only at the trail C, where the arithmetic mean deviation of the roughness profile increases with the cut height increase. The difference between the arithmetic mean deviations of the surface roughness in the trail C for the cut heights 25 and 50 mm is 13 μm.

The wood species affects the finished surface irregularity by both its natural roughness (the number and size of anatomic elements is different for each species) and the changed energy demanded for its finishing. The trails A and B are influenced mainly by the wood natural roughness, which increases in the order beech – oak – spruce.

Obviously, for the trail C also the natural roughness has its influence, however, different energy demand for the finishing of different wood species will show up there. From the power consumption point of view, most demanding is the oak finishing. This has shown up in full extent by the highest arithmetic mean deviation of the surface roughness for this wood species.

Also the feed speed effect shows up most significantly for the trail C, where the feed speed change from 0.2 to 0.4 $m \cdot min^{-1}$ means an increase of the arithmetic mean deviation of the roughness profile by 12 μm and the change from 0.4 to 0.6 $m \cdot min^{-1}$ the same deviation by 4 μm. The following linear equation can show the feed speed effect on the arithmetic mean deviation of the roughness profile:

- $R_a = 8.205 v_f + 10.99 (R^2 = 0.9274)$

The remaining two examined factors, abrasive agent mass flow rate and timber type, did not prove as statistically significant.

CONCLUSIONS

The AWJ cutting method is designed for creation of cuts with complicated shapes. The alternatives there to consist of laser cutting, saw cutting with linear reverse travel (scroll-saw based) and CNC milling. While the cut quality is comparable, the AWJ cutting method has several indisputable advantages in comparison with the mentioned alternatives. In comparison with laser, its main advantage consists on causing no burns on the cut surface as well as in the fact of insufficient number of laser devices with an output required to cut 25 mm thick material. The saws with linear reverse travel need to drill the material thoroughly and the insertion of the saw blade is arduous. The disadvantage of the CNC millers consists in the tool diameter and the related kerf width as well as the need for creation of the kerf by various passes of the tool.

Extensive research on wood and wood-based materials cutting by the mean of abrasive water jet had been carried out also by another authors, such as Gerencsér and Bejo (2007), and Barcík and Kvietková (2011). While comparing their and our conclusions, the particularity of the individual experiments (different medium pressures and abrasive agent types and materials), whose conditions affect the achieved results significantly, should be taken into account. However, we all share the conclusion on the appropriateness of the abrasive water jet method for the solid wood cutting.

The answer for the question whether the AWJ method is suitable for the solid wood cutting or not, is “Yes, it is“. However, it must be said that only under exactly defined conditions. More than at the alternative methods, it is necessary to take into account that solid wood is an anisotropic material. Due to its anisotropy, the quality indices (kerf width, finished surface irregularity) will achieve different values, depending on the cutting pattern. If necessary, these can be also eliminated by the mean of specific process conditions (feed speed, abrasive agent mass flow rate) for each cutting pattern.

The article brings several crucial findings. No materials thicker than 50 mm can be cut by the mean of AWJ method at the currently used abrasive agent maximum pressure of 400 MPa since the material is not cut through above this thickness. The surface quality equivalent to the plane milling (a requirement for the AWJ utilization as the surface finishing) is being achieved up to the thickness of 25 mm. The abrasive agent mass flow rate at 350 $g \cdot min^{-1}$ is optimal (since further increase will not cause the expected effect on the cut quality improvement). The quality criterion of the plane milling surface is met for the timber thickness up to 25 mm at any of the examined feed speeds, whereas the quality - arithmetic mean deviation of the roughness profile will range from 21 μm (at the feed speed of 250 $m \cdot min^{-1}$) to 40 μm (at the feed speed of 450 $m \cdot min^{-1}$).

ACKNOWLEDGMENT

The authors are grateful for the support of KEGA grant No. 018TU Z-4/2013, “Separation and work of wood” and by the Internal Grant Agency of Czech University of Life Sciences, Prague No. 20124311, ”The influence of cutting tool parameters on milling surface quality of wood based materials”.

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