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INVESTIGATIONS INTO THE WATERJET CUTTING OF SOLID WOOD

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ABSTRACT

Waterjet cutting is a possible alternative of traditional cutting methods. It offers an effective solution for problems like dust exposure and high noise output from wood processing machines. The examination of some technical parameters is necessary for the practical application of waterjet cutting on wood. Our project involved the assessment of moisture uptake, kerf width and surface roughness of waterjet-cut solid wood. The surface layers of wood took up much water, but they lost most of it in a short period of time. The overall moisture content did not increase significantly. Kerf width was found significantly smaller than that of traditional wood cutting tools. Kerf width decreases as the waterjet propagates into the material. This means that the edges will not be perpendicular to the face of the material. This can be corrected by a slight inclination of the nozzle. In the examined range of feed rates, surface roughness increased with increasing feed, but it always stayed significantly lower than the roughness of planed or sawn surfaces.

KEY WORDS: waterjet cutting, kerf width, moisture uptake, surface quality

INTRODUCTION

Wood and wood based products are increasingly sought after, and, in some cases, demand significantly surpasses the supply. All wood products considered, even today, the amount of waste is about 60-65% of the raw material, despite the benefits of wood panel manufacture, where much of the secondary raw materials, formerly considered waste, gets utilised (Winkler 1998). Understandably, the industry endeavours to utilise as much of the available raw material, as possible.

Wood dust generated when sawing or otherwise cutting wood and wood based materials decreases the yield significantly, and pollutes the environment. Sawdust may amount to as much as 6 to 40%, depending on raw material dimensions, product variety and technology (Vorreiter 1963).

Much of the dust generated in various wood processing plants is very small in size. Dust particles that are 7 mm or less in diameter or smaller are called respirable dusts. When they sink into the lungs upon respiration, they stay there and damage the lungs (Varga et al. 2006). Hardwood dusts are especially dangerous because of their carcinogenic nature. The EU directive 1999/38/EC pronounced hardwood dust carcinogens, calls for further research in the area and for establishing appropriate Occupational Exposure Limits (OELs) by the EU countries.

The OELs vary in different EU countries. It is 5 mg/m^3 in most countries, but is stricter, 3 mg/m^3 in Germany. Some researchers urge even stricter regulations (Innocenti 2000). In Hungary, the allowable values for total workplace concentration and respirable dust concentration are 5 mg/m^3 and 1 mg/m^3, respectively. Wood processing plants can comply with this by using multi-cyclones only, at a significant premium. Complying with these limits is a serious challenge for the wood industries.

Another drawback of sawmilling and sharpening machines is the high noise output. According to the EU Directive 2003/10/EC on the minimum health and safety requirements regarding exposure of workers to the risks arising from physical agents (noise), the average sound pressure levels in an 8-hour shift and in a week are 85 dB and 80 dB, respectively. The noise level of sawing machines is typically in the 95 to 104 range. Thus, compliance with the above limits is rather difficult when using the machines continuously.

Because of these problems, using cutting tools that do not generate dust, and whose noise output is at an acceptable level, would be desirable. One such technique is cutting wood with a high pressure waterjet that is, in addition, environment friendly and less wasteful. Some further advantages of this method are a smaller kerf width and higher levels of reliability, than those of traditional tools. Waterjet cutting is especially suitable for mass production of high-precision pieces of difficult shapes like marquetry elements, cutting wood panels and thin pieces of lumber.

Waterjet cutting may be applied on almost any type of material. Literature information is available mostly for cutting chipboard, MDF and cement bonded panels, while waterjet cutting of solid wood is less researched. The main purpose of this project was the assessment of the various aspects of solid wood waterjet cutting.

The utilisation of erosion cased by waterjets goes back several decades. American and Soviet engineers pioneered the mining use of high pressure waterjets for splitting lignite blocks in the 1930's. The aviation industry triggered further developments in the technology. Cutting materials with good technical properties that could not be processed the traditional way was possible using waterjet cutting. Towards the end of the 60's, American aircraft manufacturers used this technology for cutting fibre-reinforced, cellular and sandwich-type materials. These materials are especially vulnerable to high temperature and heavy loads, and traditional cutting torch, sawing and cutting equipment may have damaged their structure (Vlastnik 1982).

A relatively small number of publication deals with the theoretical background of waterjet cutting. The reason for this is that the theory of high pressure waterjet cutting is unclear up to date. It is a difficult process whose physical aspects (the flow of fluids in a tube, its exit from the nozzle, waterjet impact and interactions with the workpiece matter, etc.) belong to different scientific branches.

Free waterjet travelling at 2 to 4 times the speed of sound may be modelled as a solid, elastic body. Upon impact, a very large pressure is generated on a small surface area that propagates as stress waves in the material. The high pressure of the fluid generates local ruptures in the material. Generated micro-cracks deepen because of the alternating loads, and lead to a linear separation of the material. Rapid pressure fluctuations generate elastic deformation, bolstering the destruction caused by the waterjet. The effect of the fluid is more intensive than the impact of a solid body of the same weight and velocity, because of its compressibility (Vlastnik 1982).

Waterjet cutting operates with a "soft tool", which leads to problems unfamiliar to those working with traditional methods. One such problem is that the waterjet lags at the egress side compared to its entry. This may be an issue when cutting thick materials, or at corners. The solution is decreasing the feed rate when changing direction. Because there is no definite tool geometry, kerf width may vary significantly. The path of the tool needs to be corrected accordingly, to ensure accurate workpiece geometry. The divergence of the waterjet exiting the nozzle is another factor increasing the kerf width. The same waterjet becomes convergent when entering the material, i.e. kerf width decreases across the thickness of the workpiece, and the sides shall not be perpendicular to the face. This problem is less significant when cutting thinner pieces and panels, but may be problematic when working with thicker materials, like lumber.

Nowadays, when cutting hard materials, abrasive particles (granite sand) is added to the waterjet. In this case, the granite particles, rather than water, perform the actual cutting, while propelled by the water at a speed of 800 m/s. Material separation is primarily due to erosion (Maros et al. 1999).

As soon as a particle hits the material, it looses some of its energy and slows down. This leads to a deflection in its path and an increase in the angle at which it impacts the material. This, in turn, results in characteristic curved ridge lines on the cutting surface, called ribs.

The four most important factors effecting kerf geometry are waterjet pressure, feed rate, the thickness and the hardness of the workpiece. Changing these parameters leads to different kerf dimensions. Kerf width and surface quality are also influenced by jet diameter, cutting method (the use of abrasive material), the purity, hardness and quantity of water and the distance between the nozzle and the workpiece.

MATERIAL AND METHODS

Of the wood species suitable for industrial use, the most frequent ones were chosen for investigation. The various tests included oaks (*Quercus* spp.), black locust (*Robinia pseudoacacia*) beech (*Fagus silvatica*), ash (*Fraxinus excelsior*), hornbeam (*Carpinus betulus*) aspen (*Populus* spp.), linden (*Tilia* spp.), alder (*Alnus glutinosa*) and Norway spruce (*Picea Abies*). Initial investigations involved 25 mm and 50 mm thick dried lumber, as well as 15 cm diameter spruce logs. Quality cutting of thick lumber an logs was not possible with the available waterjet cutting machine. For this reason, results given in this article refer to 25 mm thick lumber exclusively, for which cutting quality was acceptable.

A variable feed Inno Cutter machine, with 3000 bar water pressure, and 5 g/min abrasive matter stream was used for the investigation. The INC (Intelligent Numeric Control) of the machine allowed accurate control of cutting direction and feed rate.

The investigation of the cutting surface included three main aspects. Water uptake, kerf width and surface roughness was evaluated, on various species, at various feed rates and in various cutting directions.

Moisture content measurements involved oak, black locust, ash, hornbeam and spruce specimens, using a VIVA 12 resistive layer moisture meter. The instrument is equipped with a stopper that ensures that electrodes are driven exactly to the desired depth. Moisture content measurements were taken near the surface (1-1.5 mm deep), and 10, 20 and 30 mm from the surface. One measurement was taken on both the side and end grain surfaces, before cutting, within 5 minutes of cutting, and 24 hours after cutting.

For kerf width measurements, incisions were made along the grain, across the grain, and at a 45° angle, using a feed rate of 300 mm/min. Ten kerf width measurements were taken with gauges, on both sides of the material. An average of the ten measurements provided the kerf width value. Kerf width measurement included black locust, ash, hornbeam, beech, linden, alder and spruce lumber.

A Pertherm S3P (PGK) type surface roughness tester, equipped with a 10 μm diameter needle, was used for roughness measurements. Surface roughness assessment involved oak, black locust, beech, aspen and spruce materials. Surfaces were cut both along and across the grain, with feed rates of 100, 200, 300, 400, 500 and 600 mm/min. In each case, the roughness profile of a 17 to 25 mm long section of each surface was recorded using the roughness tester. The needle travelled at 0.5 mm/s.

Evaluation of the recorded profiles happened using a recently developed method (Csiha and Alpár 2003, Csiha 2005). In addition to correcting the slope and waviness of the profile, this method allows the elimination of roughness caused by the vessels of large porous materials. Thus, results truly reflect the roughness arising from the cutting method only. Surface quality was evaluated on the basis of the mean roughness depth parameter (R_z).

RESULTS AND DISCUSSION

Water uptake

Fig. 1 shows a typical water uptake diagram. This figure shows that, in the vicinity of the cutting surface, moisture content increases significantly (5 to 30 %, depending on species and cutting direction) after cutting. Most of this moisture, however, leaves the surface layers in the following 24 hours.

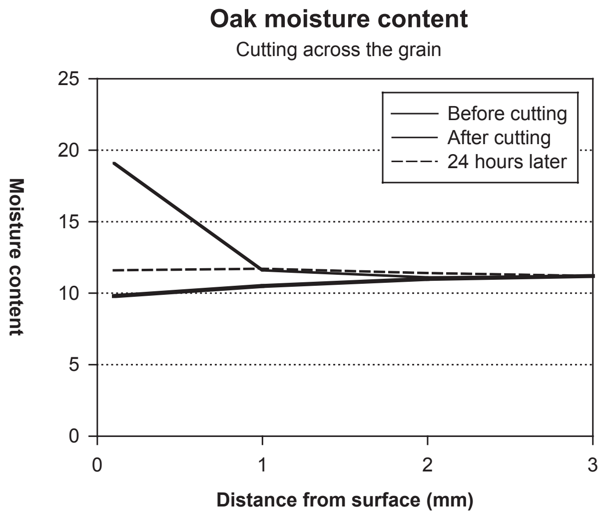

Fig. 1: Moisture content of waterjet-cut oak before and after cutting

Moisture penetration was relatively moderate in all of the species, when cutting along the grain. After cutting, moisture content measured 10 mm deep increased by no more than 2 to 4 %. Wetting was even less significant farther from the surface. In the 24 hour period after cutting, some of the moisture migrated inwards from the surface layers, especially in more permeable species (spruce, alder, beech). On average, waterjet cutting caused a 0 to 5 % moisture content increase in the examined layers.

Similar tendencies were observed when cutting across the grain, except, in softer, more permeable materials, like spruce, alder and beech, moisture penetrated deeper. In these species, a 20 to 25 % moisture percent increase occurred even at 10 mm depth. Significant moisture increase was not detected at 20 mm. In the meantime, the porosity of these species facilitated the removal of moisture in the following 24 hours. In denser, less porous species (oak, black locust), moisture did not penetrate the material significantly. Moisture content equalised after 24 hours in all of the species. The average moisture content increase was 0 to 3 %. Drying-related cracks or deformation were not visible on the cutting surfaces.

In general, though waterjet cutting, as expected, led to a moisture increase in the hygroscopic solid wood, moisture uptake was significant in the surface layers only, and even there, it was temporary. Moisture content levels out after 24 hours, and average moisture content does not increase significantly, compared to the original state.

Kerf width

Tab. 1 contains the average kerf width values measured on the examined species. As expected, kerf width is always smaller at the egress side, than at the entrance of the waterjet. Other than this, no trend is apparent from the results. Kerf width sometimes increased, in other cases decreased, or was unaffected by grain orientation. The same is true about the rate at which kerf gets narrower after the entrance of the waterjet. There was no definite species effect, either; relationships with density or other anatomical features were not detected. A more comprehensive study with larger samples may reveal some correlations, but technological parameters like feed rate, waterjet velocity and pressure are likely to be much more influential than wood species.

Values in Tab. 1 show that waterjet cutting results in kerf widths much narrower than those produced by traditional technologies. The kerf is tapering, i.e. it decreases from the entry of the waterjet towards the inside of the material. This means that cutting surface is not perpendicular to the faces. Possible practical applications will have to correct this by offsetting the angle at which the waterjet strikes the surface.

Tab. 1: Average kerf width values measured after waterjet-cutting of various species, in three different anatomical directions. (Each value is an average of ten measurements, mm)

Species	**Along the grain**		**at 45° to the grain**		**Across the grain**	
	Entry	Egress	Entry	Egress	Entry	Egress
Black locust	1,00	0,80	1,00	0,80	1,20	0,65
Ash	1,60	0,60	1,40	0,70	1,40	0,50
Hornbeam	0,90	0,45	0,90	0,50	0,90	0,50
Beech	0,90	0,50	0,80	0,45	1,00	0,50
Linden	1,10	0,75	1,10	0,65	1,10	0,40
Alder	1,70	0,70	1,25	0,55	1,25	0,55
Spruce	1,20	0,80	1,00	0,50	1,00	0,50

Surface roughness

The R_z values measured on the longitudinal and transverse cutting surfaces of various species are shown on Fig. 2 and 3 respectively. Surface roughness values varied between 15 and 85 μm depending on species and cutting direction. R_z values were mostly higher when cutting across the grain, except in the case of aspen.

Surface roughness values usually increased with higher feed rates, except when cutting oak along the grain. In some cases – e.g. when cutting aspen and black locust along the grain – roughness increased monotonously with increasing feed. In many cases, anomalies are present at 300 mm/min. Since this did not occur consistently, it was probably caused by random factors, and further investigations are probably unnecessary.

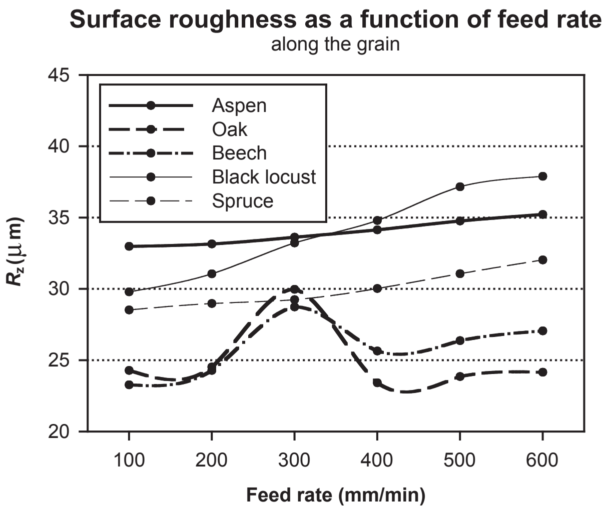

Fig. 2: Mean roughness depth values measured on cutting surfaces parallel with the grain, as a function of feed rate

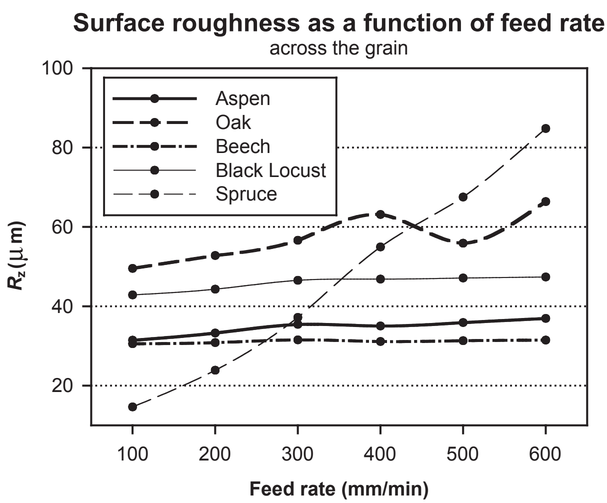

Fig. 3: Mean roughness depth values measured on cutting surfaces perpendicular to the grain, as a function of feed rate

Relationships between species and surface roughness are very hard to detect based on the measurement results. Mean roughness depth values fell in a relatively small range, between 23 and 67 μm, with the exception of cutting spruce along the grain. In this case, R_z values increased sharply and evenly as the feed rate increased from 100 to 600 mm/min. The reason for this is not clear. It may be related to the anatomical properties of coniferous species, like tracheids that may alter cutting characteristics. The causes of this phenomenon may be explained by a more in-depth study, possibly involving electronmicroscopic investigations.

Comparing the above values to those of surfaces produced by traditional cutting methods like sawing and planing, the quality of waterjet-cut surfaces was evidently much superior. Based on the results of Killic et al. (2006), the R_z values of planed aspen and beech was about 2 to 3 times higher than those of waterjet-cut surfaces. The values measured by Magoss et al. (2005) on surfaces cut by a high-speed router, are also higher than the above results.

CONCLUSIONS

Our investigations concerning the waterjet cutting of important Hungarian wood species yielded the following conclusions:

- An average capacity waterjet cutting machine is capable of cutting lumber no more than 30 mm in thickness.
- When cutting solid wood, moisture usually penetrated the surface layers only. Deeper (more than 10 mm) penetration occurs only when cutting permeable wood species across the grain. 24 hours after cutting, the moisture content in the 30 mm proximity of the surface may be 0 to 5 percent higher than the initial state. Moisture uptake seems to be relatively insignificant, presenting no serious hindrance from a practical application point of view.
- Like in other materials, kerf width decreases somewhat from the entry towards the egress side of the waterjet. Kerf width varied between 0.5 and 1.2 mm. No clear species or cutting direction effect was evident.
- The surface roughness of waterjet-cut surfaces typically increases with increasing feed. This tendency was especially strong when cutting spruce across the grain. The quality of waterjet-cut surfaces was found much better than that of planed or circular sawn wood.

Future investigations will be aimed at establishing optimal cutting parameters for various species and lumber dimensions, as well as conducting economic feasibility studies concerning cutting costs. Microscopic investigations of the cutting surfaces are also necessary.

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