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# Abrasive-Assisted High Energy Water-Jet Machining Characteristics of Solid Wood*1

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## ABSTRACT

The application of abrasive-assisted high energy water-jet was investigated as a possible new method of cutting wood. In this study the maximum cutting speeds for species of various wood density were determined and water-jet machining characteristics were investigated for sixteen Korean domestic species. The maximum cutting speed ranged from 200 to 750 mm/min. The results indicate that wood density affects machining characteristics such as maximum cutting speed, surface roughness, and kerf width. Roughness of surface generated increased and kerf width decreased as penetration depth increased.

*Keywords* : wood machining, water-jet, machining characteristics, wood density, maximum cutting speed, surface roughness, kerf width

## 1. INTRODUCTION

Machining which converts wood in its natural form into useful items is probably one of the most basic and important processes in wood industry. However, almost all the wood machining methods used today are based on many century old concepts with metal saws or tools. Advances in metallurgy and electronics have dramatically improved cutting efficiency and surface quality, but few works has been done in overcoming the basic limitations that exists in the common woodworking tools. Researches on wood machining are always dealing with the problems associated with wood substances lost as sawdust, power consumption, tool wearing or cut-surface quality. Slicing methods overcome the problems related to sawdust, but there still remain many limitations.

Bryan (1963) pointed out that machining with no chip and no deformation would be one of the ideal machining processes. If the two pieces could be separated without the loss of intermediate material, the energy requirement would be minimized since the only work done would be that necessary to form the actual surfaces desired. This ideal process could be accomplished if sufficient energy to sever all bonds could be projected along an infinitely confined path describing the surfaces to be prepared. Unfortunately this process appears not possible in reality, since it is difficult to have a con-

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ception of useful and controllable energy sources of infinitely small dimensions.

It appeared that high energy lights or liquid jets could deliver usable energy in a highly confined and controllable form to generate the prescribed surfaces. Many works has been done to employ high energy lights, LASER (Light Amplification by Stimulated Emission of Radiation), in wood machining. As Lee (1996) reported, however, laser cutting of wood remains charred surfaces, which cause problems in appearance and adhesion, since the two pieces are separated by burning and removing material in kerf. The concept of liquid jets to divide material has been applied to various materials such as metals, plastics, stones, textile, and even leather for which laser cutting is not suitable. According to Bryan (1963) and Yogov and Osipov (1962) published a paper in which speculations were firstly made in regard to the promise of water-jet wood cutting process. Bryan (1963) reported that high-velocity liquid jet could machine dense wood accurately to produce high-quality surfaces with a negligible loss of material. Komatsu (1981a) reported the relationship between jet cutting conditions and the maximum cut depth with liquid jet of aqueous solution of polyethylene oxide. He also investigated the effects of cutting conditions on the amount of liquid retention in wood, the accuracy of finishing, and roughness of machined surface (Komatsu, 1981b, 1982, 1983). While these studies included many of the important variables associated with process, there are several factors that warrant further investigation and other aspects should be studied.

The main objective of this study was to determine the maximum cutting speed for species of various wood density and investigate the effects of wood density and cutting direction on kerf width and cut-surface roughness at the maximum cutting speed determined with abrasive-assisted water-jet cutting machine.

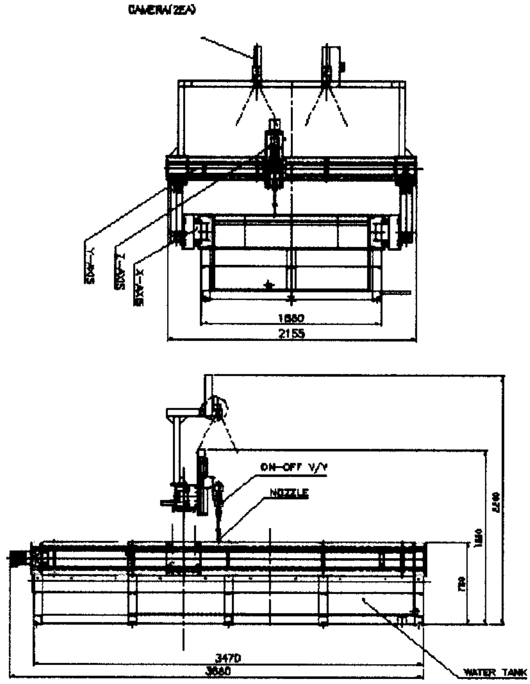

Fig. 1. A drawing of abrasive-assisted water-jet cutting machine.

## 2. MATERIALS and METHODS

Fig. 1. shows abrasive-assisted water-jet cutting machine which was constructed by Boram ITT, Inc., Korea and was controlled by CNC controller manufactured by WACOM Electronics, Co., Korea. Main specifications of this machine is as Table 1. The nozzle with opening diameter of 0.76 mm (water-jet orifice diameter 0.25 mm) was used and water-jet was impinged on the surface at an angle of 90 degrees with abrasives. Bryan (1963) found that a definite decrease in penetration occurred as the angle of incidence was increased. Abrasives accompanied with water-jet increase mass of fluid and thus enhance the impact power of jets very much. Therefore better cutting efficiency can be expected even with lower hydraulic pressure. In this experiment garnet was used as abrasives and tap water was

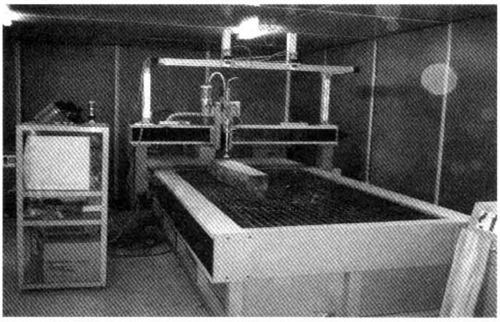

Fig. 2. Abrasive-assisted water-jet machine.

supplied as the cutting fluid.

Sixteen Korean domestic species were air-dried to about 15% moisture content and cut into 30 mm-thick flat-sawn samples to investigate the relationship between wood density and the maximum cutting speed. Air-dried volume and ovendry weight of each species was measured and nominal density was calculated for each species as Table 2 (Jung, 1998). Each species name was abbreviated to analyze test results conveniently. A hydraulic pressure of 3,000 kg/cm$^2$ was fixed to determine the maximum cutting

Table 1. Main specifications of abrasive-assisted water-jet cutting machine

| |
|---|
| Water jet high pressure pump unit |
| Power : 40 Hp |
| Intensifier type : Single |
| Maximum pressure : 4,000 kg/cm$^2$ |
| Maximum liquid flow rate : 2.9 L/min. |
| Pressure ratio : 20:1 |
| CNC controller |
| Communication : RS232C |
| Override speed : 1 ~ 100% |
| X-Y table |
| Workable table size : 1,200 × 2,400 mm |
| Control : X-Y-Z axis controllable |
| Water tank and Abrasive tank |

Table 2. Scientific and english names, nominal densities and abbreviations of sixteen Korean domestic species used as samples

| Scientific Name | English Name | Nominal Density (kg/m$^3$) | Abbreviation |
|---|---|---|---|
| *Populus maximowiczii* Henry | Japanese poplar | 364 | JP |
| *Pinus densiflora* Sieb. et Zucc. | Korean red pine | 400 | KP |
| *Maakia amurensis* Rupr. et Maxim | Amur Maakia | 482 | AM |
| *Castanea crenata* Sieb. et Zucc. | Japanese chestnut | 503 | JC |
| *Kalopanax pictus* Nakai | Castor-aralia | 533 | CA |
| *Juglans mandshurica* Maxim | Mandshurica walnut | 539 | MW |
| *Acer mono* Maxim | Painted maple | 579 | PM |
| *Fraxinus mandshurica* Rupr. | Mandshurica ash | 600 | MA |
| *Betula playtyphylla* var. *japonica Hara* | Birch | 604 | BI |
| *Prunus sargentii* Rehder | Sargent cherry | 606 | SC |
| *Meliosma myriantha* Sieb. et Zucc. | - | 635 | MM |
| *Ulmus davidiana* var. *japonica* Nakai | Japanese elm | 655 | JE |
| *Cedrela sinensis* A. Juss. | Chinese toon | 668 | CT |
| *Quercus variabilis* Bl. | Cork oak | 719 | CO |
| *Robinia pseudo-acacia* L. | Black locust | 770 | BL |
| *Betula schmidtii* Regel | - | 925 | BS |

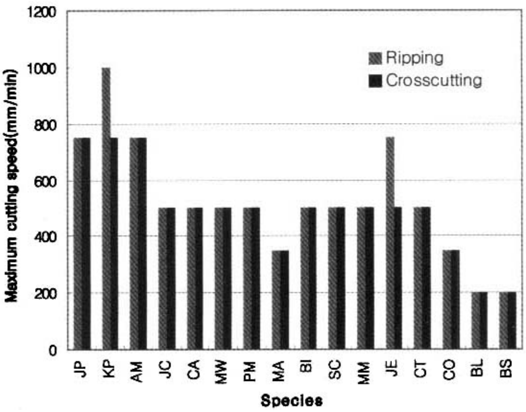


Fig. 3. Maximum cutting speeds for sixteen Korean domestic species in abrasive-assisted water-jet cutting.

speed at which each sample could be cut through and divided into two pieces. Cutting speed was increased from 50 mm/min. with the interval of 50 mm/min. and distance from nozzle to wood surface was fixed at 5 mm.

Effects of wood density and cutting direction (ripping and crosscutting) on machining characteristics such as kerf width and cut-surface roughness were also investigated at maximum cutting speed determined. Ripping means cutting direction where the direction of a water-jet agrees with the longitudinal direction of wood. Widths at top and bottom of each kerf were measured and laser- displacement sensor (resolution 10 $\mu$m) was used to estimate roughness of cut-surface at top, middle, and bottom according to root mean square ($R_{rms}$) method. Sampling length for roughness test was 10 mm.

# 3. RESULTS and DISCUSSION

## 3.1. Maximum Cutting Speed

The maximum cutting speeds in ripping and crosscutting for sixteen Korean domestic species were presented in Fig. 3. *Populus maximowiczii* Henry (JP in Fig. 3) which has the lowest density among these species could be cut through at 750 mm/min in both ripping and crosscutting while *Betular schmidtii* Regel (BS in Fig. 3) with the highest density at 200 mm/min. Therefore these results can be summarized that the maximum cutting speed should be lowered as wood density increases, except some species such as *Pinus densiflora* Sieb. et Zucc, *Fraxinus mandshurica* Rupr., and *Ulmus davidiana* var. *japonica* Nakai. Difference in density of earlywood and latewood or anatomical characteristics might be answers for these exceptions. Komatsu (1981a) reported that feed rate lower than 240 mm/min was required to cut through 3 mm-thick *Populus maximowiczii* when water-jet pressure of 3,000 kg/cm$^2$ was applied without abrasives and nozzle diameter was 0.194 mm. Thus it is clear that application of abrasives can increase water-jet cutting speed.

As reported by Lee (1996), maximum feed speed for northern red oak (*Quercus rubra* L.) and hard maple (*Aver saccharum* Marsh.) in laser crosscutting with power of 2 kW was 350 mm/min and 330 mm/min., respectively. Therefore it can be concluded that there is no significant difference in maximum cutting speed between abrasive-assisted water-jet and laser.

Considering the effect of grain orientation the lowest degree of penetration is expected to occur in the material where the jet is required to separate fibers in their strongest direction. Thus there might be a difference between ripping and crosscutting speed as Komatsu (1981a) insisted. However, somewhat large increment of cutting speed (50 mm/min) applied in this experiment could explain why no significant difference could be found in these results.

## 3.2. Roughness of Cut-surface and Width of Kerf

The quality of the surfaces produced is related to the jet diameter and cutting direction

Table 3. Roughness of surface generated by abrasive-assisted water-jet cutting of sixteen Korean domestic species

(unit : mm)

| Species | Ripping | | | | Crosscutting | | | |
|---|---|---|---|---|---|---|---|---|
| | Speed | Top | Middle | Bottom | Speed | Top | Middle | Bottom |
| JP | 750 | 0.0203 | 0.0367 | 0.0643 | 750 | 0.0187 | 0.0290 | 0.0719 |
| KP | 1000 | 0.0166 | 0.0175 | 0.0272 | 750 | 0.0532 | 0.0337 | 0.0933 |
| AM | 750 | 0.0330 | 0.0295 | 0.0436 | 750 | 0.0336 | 0.0356 | 0.0617 |
| JC | 500 | 0.0297 | 0.0326 | 0.0766 | 500 | 0.0346 | 0.0438 | 0.0491 |
| CA | 500 | 0.0342 | 0.0613 | 0.1592 | 500 | 0.0439 | 0.0605 | 0.0640 |
| MW | 500 | 0.0259 | 0.0226 | 0.0339 | 500 | 0.0265 | 0.0317 | 0.0719 |
| PM | 500 | 0.0201 | 0.0290 | 0.0785 | 500 | 0.0192 | 0.0190 | 0.0376 |
| MA | 350 | 0.0201 | 0.0225 | 0.0593 | 350 | 0.0228 | 0.0238 | 0.0274 |
| BI | 500 | 0.0163 | 0.0160 | 0.0192 | 500 | 0.0238 | 0.0224 | 0.0586 |
| SC | 500 | 0.0270 | 0.0238 | 0.0429 | 500 | 0.0178 | 0.0209 | 0.0455 |
| MM | 500 | 0.0237 | 0.0235 | 0.0370 | 500 | 0.0207 | 0.0187 | 0.0484 |
| JE | 750 | 0.0327 | 0.0289 | 0.0496 | 500 | 0.0277 | 0.0354 | 0.0463 |
| CT | 500 | 0.0266 | 0.0364 | 0.0807 | 500 | 0.0348 | 0.0281 | 0.0976 |
| CO | 350 | 0.0289 | 0.0335 | 0.0760 | 350 | 0.0205 | 0.0278 | 0.0887 |
| BL | 200 | 0.0591 | 0.0810 | 0.1453 | 200 | 0.0383 | 0.0448 | 0.0819 |
| BS | 200 | 0.0230 | 0.0235 | 0.0383 | 200 | 0.0205 | 0.0170 | 0.0429 |

and in general, the dense woods and the latewood portions of the softwoods show much smoother surfaces than the material of low specific gravity. The results presented in Table 3, however, do not follow that principles since cutting speed was not same for each species. Rearrangement of the results for only six species which were tested at the same cutting speed 500 mm/min explains the relationship between wood density and cut-surface quality clearly as shown in Fig. 4.

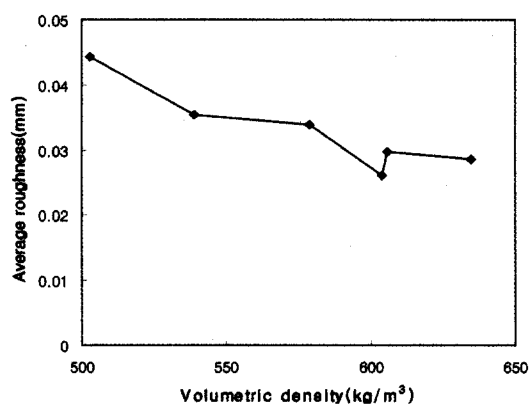


Fig. 4. Relationship between density of sixteen Korean domestic species and average roughness of surface generated by abrasive-assisted water-jet cutting.

Bryan (1963) indicated that material removed was separated from that remaining by shear and/or tensile failure through the microscopic examinations of the surfaces generated by water-jet cutting. If the velocity and energy of water-jet are maintained constant along the path, accurate surface can be obtained in the thickness direction. Unfortunately the initial cutting energy of a water-jet is reduced gradually as penetration depth increases. Therefore kerf width at surface was wider than that at bottom as presented in

Table 4. Kerf widths at top and bottom generated by cutting with abrasive-assisted water-jet for sixteen Korean domestic species

(unit : mm)

| Species | Ripping | | Crosscutting | |
|---|---|---|---|---|
| | Top | Bottom | Top | Bottom |
| JP | 1.45 | 0.90 | 1.45 | 0.90 |
| KP | 1.10 | 1.35 | 1.30 | 1.35 |
| AM | 1.50 | 1.55 | 1.45 | 1.50 |
| JC | 1.50 | 1.00 | 1.50 | 1.15 |
| CA | 1.55 | 1.45 | 1.60 | 1.00 |
| MW | 1.50 | 1.20 | 1.65 | 1.10 |
| PM | 1.20 | 1.20 | 1.50 | 1.15 |
| MA | 1.60 | 1.20 | 1.70 | 1.30 |
| BI | 1.60 | 1.30 | 1.45 | 1.40 |
| SC | 1.60 | 1.30 | 1.50 | 1.00 |
| MM | 1.50 | 1.00 | 1.50 | 1.15 |
| JE | 1.60 | 1.45 | 1.50 | 1.10 |
| CT | 1.49 | 0.90 | 1.40 | 0.90 |
| CO | 1.60 | 1.60 | 1.45 | 1.20 |
| BL | 1.45 | 1.45 | 1.45 | 1.20 |
| BS | 1.25 | 0.85 | 1.60 | 0.85 |
| Average | 1.47 | 1.23 | 1.50 | 1.14 |

Table 4. On the other hand Fig. 5 depicts that surface roughness increased as penetration depth increased as Komatsu (1983) presented.

## 4. CONCLUSIONS

Machining characteristics of air-dried various Korean domestic species were investigated with abrasive-assisted water-jet machine. The maximum cutting speed ranged from 200 mm/min to 750 mm/min and application of abrasives increased cutting speed. However this speed was much lower than that of conventional cutting methods with cutting tools such as saws or knives. Therefore it is necessary to find the

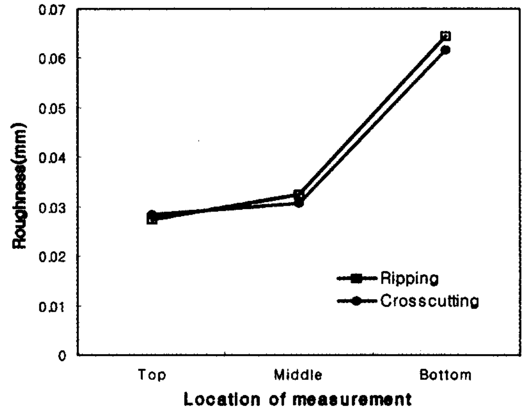


Fig. 5. Average roughness at various depths of kerf produced by abrasive-assisted water-jet cutting for sixteen Korean domestic species.

applications which will make water-jet cutting feasible in wood industry, such as cutting the complicate patterns in wood furniture industry.

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