Influence of Processing Parameters on the Surface Roughness of Solid Wood Cut by Abrasive Water Jet

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The surface roughness of pine, beech, and oak wood cut in the abrasive water jet (AWJ) system was evaluated for different processing parameters. Wood specimens were prepared in thicknesses of 18, 36, and 54 mm in both tangential and radial directions. Then the specimens were cut, applying three different feed speeds (50, 100, and 200 mm/min), three different abrasive flow rates (200, 300, and 450 g/min), and two different cutting liquid pressures (300 and 380 MPa) with the AWJ system. The R_a and R_z roughness values were higher in the tangential cut for pine and oak specimens and in the radial cut for beech wood. Roughness values increased in all specimens with increases in the AWJ feed speed and the wood thickness. In contrast, with increased amounts of abrasive, R_a and R_z values of the specimens decreased and surface smoothness tended to increase. Roughness values of pine and oak specimens generally decreased due to the increase in liquid pressure. However, an increase in the roughness of the beech specimens was determined. As a result, the feed speed and wood thickness were the most influential parameters on the roughness of specimens. In contrast, the cutting direction and liquid pressure showed less importance on the roughness.

Keywords: Abrasive water jet; Processing parameter; Surface roughness; Wood material

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INTRODUCTION

The surface quality of wood and wood-based materials is an important criterion in terms of the costs and aesthetic properties of final products. Surface roughness is a basic factor used to determine the surface quality of wood products (Kılıç 2015; Pinkowski *et al.* 2018). The surface roughness of treated wood products significantly affects later processes such as bonding and finishing (Richter *et al.* 1995; Hiziroğlu *et al*. 2014; Söğütlü *et al.* 2016; Salca *et al.* 2017; Söğütlü 2017). The surface quality of the processed wood is affected by many factors such as the anatomical properties, density, moisture, processing method, properties of the process, and processing parameters (Örs and Gürleyen 2002; Kılıç *et al*. 2006; Budakçı *et al.* 2011; Tiryaki 2014; Sofuoğlu and Kurtoğlu 2015; Hazır *et al*. 2017; İlçe 2018; Pinkowski *et al.* 2018).

Conventional machinery used in the woodworking industry for the processing of wood and wood-based materials is losing importance daily. Thanks to developing technology, these machines have been replaced with fully automatic and computer-controlled ones. These next-generation machines used in production are of great importance for businesses in reducing product costs, as they enable the reduction of the workforce, acceleration of the production line, and the saving of time. They also enable greater product variety.

Different geometric figures and complex shapes are often preferred in the manufacture of furniture, decoration, and structural joinery products. Some special cutting methods must be applied for the quick and easy fabrication of the products with this feature. Four possible basic processing methods have been specified in the material cut. These methods are saw cutting with linear reverse travel (scroll-saw based), computer numerical controlled (CNC) milling, laser cutting, and abrasive water jet cutting (Kminiak and Gaf 2014). There is a growing interest in the development of processing methods (milling, cutting, *etc.*) to increase the value and the worth of the wood materials. Recently, water jet technology has been one of the promising options in the processing of wood and wood-based materials (Wang 2012).

Water jet technology is a new non-conventional industrial method that can be used for cutting materials of different properties. The principle of water jet processing technology can be explained as cutting of the workpiece by means of a fluid that mechanically acts on the material (Barcik *et al.* 2011a; Kvietkova *et al.* 2014; Oh and Cho 2014; Li *et al.* 2015). According to different cutting features in water jet technology, two practical methods are used. They are cutting with a pure water jet (WJ) and cutting with an abrasive water jet (AWJ) (Kvietkova *et al.* 2014; Li *et al.* 2015). Many different materials can be cut using WJ and AWJ methods (Hashish 1987; Zhong and Han 2002; Akkurt *et al.* 2004; Aydın *et al.* 2011; Li *et al.* 2013; Shanmughasundaram 2014; Hutyrová *et al.* 2016). However, AWJ technology, which is an improved form of the WJ method for processing harder materials, such as metal, ceramic, and wood, is a more efficient cutting method (Saraçyakupoğlu 2012). The AWJ machining is a mechanical method in which abrasive particles, such as silica sand, garnet, aluminum oxide, silicon carbide, *etc.*, are entrained in high speed waterjet to erode materials from the surface of material (Sreekesh and Govindan 2014). AWJ technology is very suitable for automation, and highly flexible for the cutting of complex shapes from many different materials (Youssef 2016).

The WJ and AWJ technologies are widely used in many industries, such as aerospace engineering, military engineering, automotive industry, building materials and decoration elements, food processing, and underground mining (Li *et al.* 2018a). These technologies have benefited from a useful cutting method that can be used for cutting many different materials such as marble, metal, glass, plastic, wood, fabric, and paper (Akkurt 2004). It is a simple, clean, and reliable technology, and therefore it serves as an alternative to other cutting methods (Barcik *et al.* 2011b; Kvietkova 2014). Furthermore, water jet technology is especially suitable for mass production of high-precision pieces of difficult shapes such as marquetry elements, cutting wood panels, and thin pieces of lumber (Gerencsér and Bejó 2007). In processing precious wood, the use of water jet technology has the significant advantages of excellent cutting quality, high efficiency, low cost, environmental protection, and simple system operation, which can reasonably increase utilization rate of the wood (Hou *et al.* 2014; Ábrahám *et al.* 2015; Li *et al.* 2018b). In addition, water jet cutting offers an effective solution to problems such as dust exposure and high noise in conventional woodworking machines (Gerencsér and Bejó 2007). Moreover, in the processing of composite materials produced with synthetic resins and natural fibers, problems arise when the plastic matrix melts and sticks on the cutting tools. This problem can be solved by using water jet technology (Hutyrová *et al.* 2016).

In this study, solid wood specimens were cut using the AWJ system by applying different process parameters. The effects of variables, such as wood thickness, cutting direction, feed speed, abrasive flow rate, and water pressure, on the R_a and R_z roughness values of the wood specimens were analyzed. Thus, it was aimed to determine the most suitable process parameters to obtain smoother surfaces in wood specimens.

EXPERIMENTAL

Materials

In this study, Scotch pine (*Pinus sylvestris* L.), Eastern beech (*Fagus orientalis* Lipsky), and sessile oak (*Quercus petraea* Liebl.) wood, which are widely used in the woodwork industry and furniture-decoration applications, were used. Wood materials, which have a moisture content of approximately 12% to 14%, were selected randomly from a timber company in Düzce, Turkey. Wood specimens were cut from the sapwood in draft sizes of 550 mm × 65 mm × 65 mm (longitudinal direction × tangential direction × radial direction) and in sufficient numbers. Afterwards, the specimens were held in a conditioning cabin (relative humidity (RH) 65 ± 3% and 20 ± 2 °C) until they reached a stable weight, after which they were cut to the dimensions of 250 mm × 54 mm (L × T or R) and in three different thicknesses (18 mm, 36 mm, and 54 mm) in both tangential and radial directions. The air-dry density values of wood specimens were measured as 541 kg/m^3 for pine, 678 kg/m^3 for beech and 736 kg/m^3 for oak (ISO 13061-2 2014). To keep the wooden specimens stable during the cutting process with AWJ, as shown in Fig. 1, guide holes (diameter: 8 mm) were drilled 20 mm inside the cross-sectional edges of the wood.

Cutting of wood specimens in AWJ system

Both CNC and a console-type AWJ machine (S-HP Consol; CT Cutting Technologies and Machinery Ind. Inc., Tuzla, Istanbul) were used to cut wood specimens with different parameters. Thickness and cutting direction of the wood specimens and the parameters applied in the cutting process are shown in Table 1.

Table 1. Machining Parameters in AWJ Cutting

Wood Thickness (mm)	18, 36, 54
Wood Cutting Direction	Tangential, radial
Feed Speed (mm/min)	50, 100, 200
Abrasive Mass Flow Rate (g/min)	200, 300, 450
Liquid Pressure (MPa)	300, 380
AWJ Nozzle Diameter (mm)	0.76
AWJ Nozzle Length (mm)	80

To prevent the movement and vibration of the test specimens during the cutting process, the specimens to be cut were fixed by being placed between previously prepared molds. Cutting operations started and ended in the guide holes previously drilled 20 mm inside the cross-sectional edges of the specimens (Fig. 1). In cutting operations, the AWJ nozzle was adjusted to be 3 mm up the specimen surface. Garnet (7.5 to 8 Mohs) was used as the abrasive in the water jet.

After the cutting process, the excess part on the ends of the wood specimen was cut using a circular saw machine. Then, the specimens were kept until they reached constant weight under 20 ± 2 °C temperature and 65 ± 3% RH conditions, and specimen surfaces were prepared for roughness testing.

Fig. 1. Cutting wood specimens in AWJ system

Methods

Determination of surface roughness properties

Surface roughness of wood specimens was determined using a Mitutoyo SurfTest SJ-301 (Mitutoyo® Inc., Kawasaki, Japan) device (Fig. 2). The R_a, R_y, and R_z parameters are generally used in the numerical expression of the surface roughness in wood material. The R_a and R_z parameters were measured to evaluate the surface roughness of the specimens according to ISO 4287 (1997). The R_a is the arithmetic mean of the absolute values of the profile departures, and R_z is the arithmetic mean of the 10-point height of irregularities.

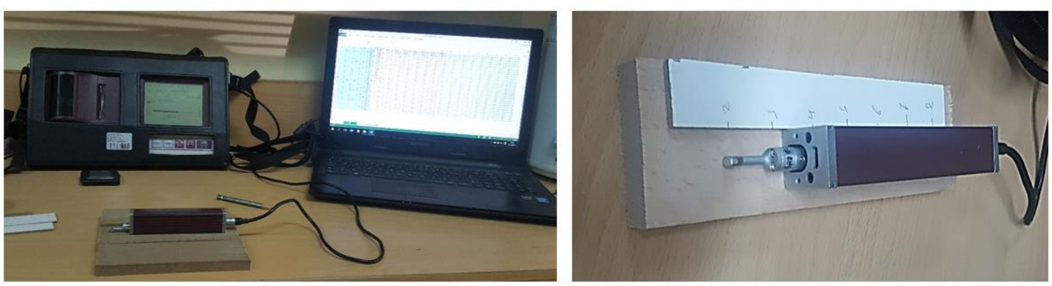

Fig. 2. Roughness measuring device

After setting the roughness measuring device (resolution/range 0.01 μm/10 μm) to a measuring speed of 15 mm/min, a measuring step length of 2.5 mm, and a measurement number of 5, roughness values were measured from eight different points (n = 8) at equal intervals on a specific line of the specimen surfaces. The reference lines in the measurements according to the thickness of the wooden specimens are shown in Fig. 3. However, because deep marks or fluctuations occurred after the AWJ cutting on specimen surfaces prepared in 54 mm thickness, roughness measurement could not be taken on the line determined in these specimens. For this reason, roughness measurements were taken on the 36 mm depth line instead of 45 mm in all specimens prepared with a thickness of 54 mm. Roughness measurements were taken in the direction of wood fibers. Approximately 864 measurements (wood thickness of 3 × cutting directions of 2 × feed speed of 3 × abrasive flow rate of 3 × liquid pressure of 2 × measurement repetitions of 8) were made for each wood species, and a total of 2592 measurements (864 × wood species of 3) were taken.

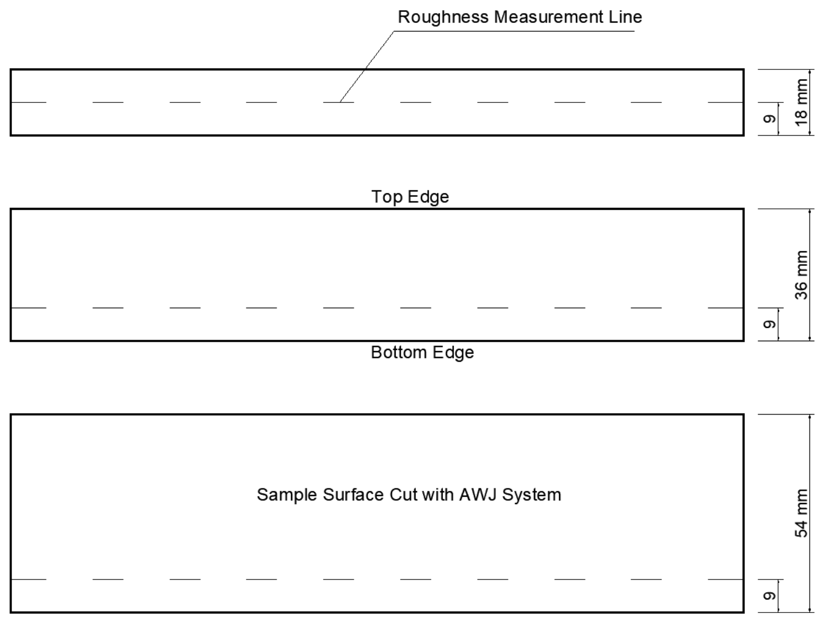

Fig. 3. Roughness measurement lines (locations) according to wood thicknesses

Statistical analyses

An MSTAT-C 2.1 software program (Michigan State University, East Lansing, MI, USA) was used for statistical evaluations. Analysis of variance (ANOVA) tests were performed to determine the effect of selected machining parameters on surface roughness properties of wood specimens at the 0.05 significance level. Significant differences between the variables were compared using Duncan's test.

RESULTS AND DISCUSSION

The ANOVA results of surface roughness measurements from pine, beech, and oak specimens cut with different processing parameters in the AWJ cutting system are given in Table 2. The results showed that the effect of cutting direction and thickness, feed speed, abrasive mass flow rate, and cutting liquid pressure factors on R_a and R_z roughness values for each wood species was statistically significant ($p \leq 0.05$). Only the effect of cutting liquid pressure on R_a values of oak specimens was found to be insignificant.

Duncan's one-way test results conducted for comparisons of the means of R_a and R_z values in pine, beech, and oak wood specimens cut with different processing parameters in AWJ cutting are given in Tables 3 and 4. In terms of cutting direction, in tangential cut pine and oak wood specimens, and in radial cut beech wood specimens the R_a and R_z values were higher. It can be said that the natural anatomical properties of the wood and the surface texture affected the results. In the literature, it has been stated that the roughness of the wood is dependent primarily on anatomical properties, and secondarily on the machine used in the processing of the wood, process parameters, process methods, and moisture (Sieminski and Skarzynska 1987; Tiryaki 2014). As for wood thickness, the lowest R_a and R_z values were found in 18-mm specimens, while the highest were found in 54-mm specimens. As seen in Figs. 4 and 5, R_a and R_z values increased due to the increase in thickness in wood specimens cut using the AWJ system. Compared to the 18-mm-thick pine, beech, and oak specimens, the R_a value of the 54-mm specimens increased 32%, 41%, and 49%, respectively; and the R_z value increased 30%, 38%, and 46%, respectively. The increases in R_a and R_z roughness values may have resulted from the wider angle formed by the abrasive particles and high-pressure water coming out of the water jet nozzle, and the irregular spread of these particles. In addition, the decrease in the velocity of the high-pressure water with abrasive additive applied on the surface of the material over time may have also affected the results. In previous studies, it was reported that as the depth the water jet beam penetration was increased, the deflection amount also increased; and accordingly, as the thickness of the specimens was increased, the roughness on its surface turned into wavy or linear traces. Additionally, it was stated that the decrease in the sharpness of the abrasive particles and fluid pressure in the cutting process using AWJ inevitably results in the emergence of a rougher surface (Ohlsson 1995; Karakurt *et al.* 2010).

Table 2. ANOVA Results for R_a and R_z Parameters of Wood Specimens

Wood Species	Source	Surface Roughness			
		R_a		R_z	
		F-ratio	p-value	F-ratio	p-value
Scotch Pine	Cutting direction and thickness	189.1768	0.0000*	197.7674	0.0000
	Feed speed	846.6036	0.0000	832.8585	0.0000
	Abrasive flow rate	24.4491	0.0000	28.5232	0.0000
	Liquid pressure	39.8036	0.0000	36.9215	0.0000
Eastern Beech	Cutting direction and thickness	174.3728	0.0000	188.8645	0.0000
	Feed speed	619.7935	0.0000	682.6197	0.0000
	Abrasive flow rate	64.3292	0.0000	68.1125	0.0000
	Liquid pressure	32.0913	0.0000	52.0216	0.0000
Sessile Oak	Cutting direction and thickness	286.6223	0.0000	362.6666	0.0000
	Feed speed	455.9889	0.0000	587.8457	0.0000
	Abrasive flow rate	49.2667	0.0000	46.4956	0.0000
	Liquid pressure	1.7245	NS	7.1587	0.0076

* Significant at 95% confidence level; NS: not significant

In terms of feed rate in the AWJ cutting, in all wood species the highest R_a and R_z averages were obtained with the feed rate of 200 mm/min, and the lowest was obtained with the feed rate of 50 mm/min (Tables 3 and 4). The R_a and R_z roughness values measured in wood specimens were generally increased due to the increase in feed rate of the AWJ system (Figs. 4 and 5). Compared to the feed rate of 50 mm/min, in the pine, beech, and oak specimens cut with a feed rate of 200 mm/min, the R_a value increased 47%, 53%, and 41%, respectively, and the R_z values increased 43%, 50%, and 40%, respectively. It can be said that the cutting process became more difficult as the feed rate of the AWJ system increased and the rate of pressurized water and abrasive applied on the unit surface decreased, which affected the results. The feed rate in water jet cutting is defined according to the period in which the material is exposed to abrasion or cutting effect. A decrease in the feed rate means that a part of the material is subjected to the water jet effect for a longer time. Thus, on the cut surface, the number of abrasive particles per unit volume increases and accordingly, the surface quality improves (Ohlsson 1995; Karakurt *et al.* 2010). In a study where the surface roughness of solid wood materials cut using the pure WJ was investigated, it was stated that the surface roughness also increases with the increase of the feed rate of the WJ (Gerencsér and Bejó 2007). Additionally, studies on different materials cut using the AWJ system reported that the surface roughness values increase due to the increase in the feed rate (Akkurt *et al.* 2004; Hascalik *et al.* 2007; Aydın *et al.* 2011; Saraçyakupoğlu 2012).

Table 3. Duncan's Test Results for Mean of R_a Values

Factor	Scotch Pine		Eastern Beech		Sessile Oak	
	Mean (µm)	SG	Mean (µm)	SG	Mean (µm)	SG
Cutting Direction and Thickness (mm)						
R-18	7.13	e	5.67	e	5.56	f
R-36	7.67	d	6.53	c	6.54	d
R-54	8.97	b	8.01	a	7.87	b
T-18	7.02	e	5.27	f	5.86	e
T-36	7.90	c	6.15	d	6.87	c
T-54	9.75	a	7.41	b	9.12	a
Feed Speed (mm/min)						
50	6.71	c	5.21	c	5.80	c
100	7.66	b	6.34	b	6.94	b
200	9.85	a	7.97	a	8.17	a
Abrasive Flow Rate (g/min)						
200	8.37	a	6.98	a	7.29	a
300	8.03	b	6.46	b	7.08	b
450	7.83	c	6.08	c	6.53	c
Liquid Pressure (MPa)						
300	8.28	a	6.32	b	7.01	a
380	7.87	b	6.69	a	6.93	a

SG: statistical group (different letters denote a significant difference); R: radial; T: tangential

Regarding abrasive flow rate in AWJ system, in all wood species, the highest averages of R_a and R_z were determined with an abrasion rate of 200 g/min, and the lowest was determined with an abrasion rate of 450 g/min (Tables 3 and 4). As can be seen in Figs. 4 and 5, as the amount of abrasive added to the pressurized liquid increased, the overall R_a and R_z roughness values of the wood specimens were observed to decrease. Accordingly, the level of surface smoothness of the specimens tended to increase. Compared to the abrasive flow rate of 200 g/min, in the pine, beech, and oak specimens cut with an abrasive flow rate of 450 g/min, R_a value decreased 6%, 13%, and 10%, respectively, and R_z value decreased 7%, 12%, and 9%, respectively. It can be said that, in the process of cutting using AWJ, the increase in the effectiveness of the abrasive particles as a result of increasing the amount of these abrasive particles and decreasing the amount of water used had an important effect on the results. In addition, the decrease in the fiber breaks and deformations occurring on the material surface during the cutting process as a result of the increase in the amount of abrasive per unit area may have affected the results. In a previous study, it was stated that the increased amount of abrasive in the AWJ cutting system meant an increased number of abrasive particles to be applied to the unit area, thus reducing the roughness or waviness to occur on the surface was expected (Karakurt *et al.* 2010). In contrast, it was stated that the effect of feed rate, abrasive flow rate, and the material thickness on the surface roughness of the medium-density fiberboards cut using AWJ is insignificant (Kvietkova *et al.* 2014).

Table 4. Duncan's Test Results for Mean of R_z Values

Factor	Scotch Pine		Eastern Beech		Sessile Oak	
	Mean (µm)	SG	Mean (µm)	SG	Mean (µm)	SG
Cutting Direction and Thickness (mm)						
R-18	39.25	d	32.39	e	32.10	f
R-36	42.36	c	35.99	c	37.05	d
R-54	48.98	b	44.49	a	44.36	b
T-18	39.15	d	30.07	f	33.73	e
T-36	43.14	c	34.52	d	39.37	c
T-54	53.26	a	41.51	b	51.92	a
Feed Speed (mm/min)						
50	37.35	c	29.49	c	33.21	c
100	42.36	b	35.77	b	39.58	b
200	53.36	a	44.22	a	46.48	a
Abrasive Flow Rate (g/min)						
200	45.80	a	38.93	a	41.21	a
300	44.49	b	36.27	b	40.41	b
450	42.78	c	34.28	c	37.65	c
Liquid Pressure (MPa)						
300	45.35	a	35.31	b	40.18	a
380	43.36	b	37.67	a	39.33	b

SG: statistical group (different letters denote a significant difference); R: radial; T: tangential

With respect to cutting liquid pressure in the AWJ cutting, in pine and oak specimens, the average values of R_a and R_z were lower under a pressure of 380 MPa compared to a pressure of 300 MPa. However, the difference between R_a values in oak specimens was statistically insignificant. In beech specimens, the average values of R_a and R_z were lower under a pressure of 300 MPa compared to a pressure of 380 MPa (Tables 3 and 4). Depending on the increase in cutting liquid pressure, in pine and oak specimens, the R_a and R_z roughness values generally tended to decrease. In beech specimens, the opposite was true (Figs. 4 and 5).

The textural structure of the beech specimens may have had an effect on the results. In pine and oak specimens cut under a pressure of 380 MPa, compared to 300 MPa, the R_a values decreased 5% and 1%, respectively, and the R_z values decreased 4% and 2%, respectively. In beech specimens, with the increase in the liquid pressure, the R_a and R_z values increased 6% and 7%, respectively. In a previous study, it was reported that the roughness is somewhat reduced by increasing liquid pressure during the cutting of recombinant bamboo using AWJ (Li *et al.* 2015). Xie *et al.* (2020) determined that the factors affecting the surface roughness of red oak and bamboo specimens cut with AWJ system are ranked as follows: cutting pressure > feed rate > abrasive flow rate > target distance > air-dry density. In addition, it has been stated that the liquid pressure has the most important effect on the surface quality of three hardwood types (okan, iroko, and merbau) cut using AWJ (Wang 2012). In contrast, it is stated that the cutting liquid pressure is more effective against the occurrence of traces in the form of lines or waviness on the surface rather than the surface roughness of the material. It was also reported that the waviness rate on the surface increases if the liquid pressure increases but does not cause a significant change in the surface roughness (Shipway *et al.* 2005; Karakurt *et al.* 2010).

Fig. 4. The R_a values of pine, beech, and oak woods cut with different processing parameters in the AWJ system

Fig. 5. The R_z values of pine, beech, and oak woods cut with different processing parameters in the AWJ system

CONCLUSIONS

1. The effect of different processing parameters on the surface roughness properties of pine, beech, and oak woods cut with AWJ cutting system was investigated. With the increase in the thickness of the wood specimens, the R_a and R_z values also increased. Compared to the specimens of 18 mm, in the specimens with a thickness of 54 mm the R_a and R_z increased 49% and 46%, respectively. Additionally, the R_a and R_z were determined to be higher in the tangentially cut specimens for pine, oak wood, and in the radially cut specimens for beech wood.
2. For all wood types, the R_a and R_z roughness values increased due to the increase in the AWJ system feed rate. Compared to the feed rate of 50 mm/min, the R_a and R_z values of the specimens cut at a feed rate of 200 mm/min increased 53% and 50%, respectively.
3. As a result of the increase in the amount of abrasive added to the pressurized water, R_a and R_z decreased in general and surface smoothness of the specimens increased. Compared to the abrasive flow rate of 200 g/min, the R_a and R_z values of the specimens processed at an abrasive flow rate of 450 g/min decreased 13% and 12%, respectively.
4. Depending on the increase in cutting liquid pressure, the R_a and R_z values generally tended to decrease in pine and oak specimens. There was an increase in beech specimens. In pine and oak specimens cut under a pressure of 380 MPa compared to 300 MPa, the R_a and R_z values decreased up to 5% and 4%, respectively. In beech specimens, with the increase in the liquid pressure the R_a and R_z values increased 6% and 7%, respectively.
5. As a result, while the feed rate and wood thickness factors on the roughness values of wood specimens cut using the AWJ system have primary importance, the cutting liquid pressure factor has the least importance.

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