EFFECT OF CUTTING PARAMETERS ON DUST EMISSION AND SURFACE ROUGHNESS DURING HELICAL PLANING RED OAK WOOD

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Abstract. Cutting parameters can influence the chip thickness and resulting dust emission and surface quality during wood machining. The purpose of this study was to evaluate the effect of cutting parameters on the airborne dust emission (0.1-15 μm) and surface roughness produced by helical planing red oak wood. Two cutting depths (0.5 and 1.0 mm) and eight feed speeds (from 6 to 20 m/min) were combined to obtain four average chip thicknesses (from 0.10 to 0.22 mm). The results showed that dust emission decreases as average chip thickness increases. Dust emission also increased for the higher cutting depth but for thinner chips (0.10 mm thick). For thicker chips, dust emitted was similar for the two studied cutting depths. Regression models for estimating dust emission for each particle size fraction as a function of average chip thickness and cutting depth were developed. Furthermore, higher values of average chip thickness produced higher surface roughness. The best helical planing condition was obtained when using 0.5-mm cutting depth, 0.18-mm average chip thickness, and 16 m/min feed speed. This condition was the fastest feed speed allowable to obtain the best surface quality while minimizing dust production.

Keywords: Average chip thickness, cutting depth, wood dust, surface roughness.

INTRODUCTION

Dust produced during the usual operations of wood machining may not be totally captured by the devices integrated to machinery, and thus can be dispersed in the workshops (Dessagne et al 2006). Concerns have been raised by the repeated exposure to wood dust, which can cause respiratory problems, like asthma and bronchitis, as well as skin allergies in woodworkers (Hinnen et al 1995; Crépy et al 2007; Monier et al 2008; Krief et al 2008; Ramroth et al 2008; Rao and Balachandran 2010). Furthermore, several international research organizations have classified wood dust as a potential carcinogen (IARC 1995; ACGIH 2008). The health effects from exposure to wood dust are mainly due to particular components of wood, the physical and mechanical nature of dust particles, and the size and amount of dust itself (Bulletin n. 238 2005). Thus, the location of dust in the human respiratory system depends on the size and concentration of wood particles and their resistance to airflow (IARC 1995; Maynard and Jensen 2001; NTP 2016).

In terms of risk management, prevention is prioritized as: 1) the reduction of dust levels in the working environment and 2) the information campaigns to workers (SFMT 2011). The dustiness of the working environment depends on machine type, machining parameters, quality of the collector system, wood species, and conditions of the surrounding air (Palmqvist and Gustafsson 1999; Kos et al 2004; Rautio

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et al 2007; Ratnasingam et al 2009; Welling et al 2009; Fujimoto et al 2011). Concerning the dust size, large particles settle quickly and are easier to capture by dust collection systems. In contrast, the finest particles can escape from most collection systems. Thus, the optimization of particle size to minimize and/or decrease the dust emissions during wood machining is of great interest.

Several studies have been conducted on the influence of the various machining processes on wood dust emission. The main processes studied are sanding, sawing, and planing. Cutting parameters act directly in the formation of wood chips and fine particles. Parameters as material type, wood species, wood moisture content, average chip thickness, cutting speed, feed speed, cutting angles, feeding direction, and sandpaper grit size have been investigated (Palmqvist and Gustafsson 1999; Kos et al 2004; Rautio et al 2007; Ratnasingam et al 2009; Saejiw et al 2009; Welling et al 2009; Fujimoto et al 2011). Among these parameters, average chip thickness was one of the most significant affecting the amount of dust generated during wood machining (Palmqvist and Gustafsson 1999; Kos et al 2004; Rautio et al 2007). Chip thickness must be optimized to reduce its impact on the production of wood dust. Thickness can be manipulated by setting different cutting parameters as feed speed, rotational speed, number of knives on the cutterhead, cutting depth, and cutting diameter (Koch 1964). Rautio et al (2007) recommended higher feed speeds to reduce fine dust generated during milling of different wood materials. In fact, as feed speed increases, chip thickness increases.

It is known that sanding is one of the most common surfacing method used to prepare wood surfaces prior to coating. However, this process produces finer dust compared with other machining process (Chung et al 2000). Under this context, helical planing has been proposed as an alternative method to reduce the need for sanding during wood finishing (de Moura and Hernández 2006a, 2006b; Hernández and Cool 2008a, 2008b; Cool and Hernández 2011). This process is less noisy than conventional planing and improves the surface quality (Stewart and Lehmann 1974). Quality of surfaces is often assessed by means of roughness measurements. A good finish is normally associated with lower roughness (de Moura et al 2010; Cool and Hernández 2011). However, the particular effects of chip thickness and cutting depth on dust emissions and surface roughness during helical planing have not yet been investigated. As regard to wood species, red oak (*Quercus rubra* L.) is one of the most important trees in North America. Its wood is largely used for furniture, flooring, interior trim, and veneer. However, wood dust of the genus *Quercus* has been associated with several adverse health effects (Research BC 1985; OSHA 1999; ACGIH 2008). The aim of this study was to determine the effect of cutting parameters on dust emission and surface roughness during helical planing red oak wood. Regression models for each dust fraction were developed in an attempt to estimate dust emissions during helical planing of this species.

MATERIALS AND METHODS

Materials

Red oak (*Quercus rubra* L.) wood was chosen for this study due to its economic importance and the negative health effects resulting from exposure to dust during its machining. Experiments were carried out with 30 flat-sawn boards. The equilibrium moisture content of boards was 8%, which was achieved in a conditioning room set at 20°C and 40% RH. The average density and standard deviation of boards were 694 and 53 kg/m^3, respectively, at 8% of moisture content. After conditioning, boards were cut to 900-mm length, 60-mm width, and 20-mm thickness in the longitudinal, tangential, and radial directions of wood, respectively.

Machining Treatments

The effects of chip thickness and cutting depth, on the airborne dust emission and surface roughness during helical planing, were studied. Helical planing treatments were performed with a Casadei R63H3 planer. The rake and helix angles were 30° and 14°, respectively. Only one of the two knives on the cutterhead was set to produce the final surface. The second knife served as counterbalance with a slightly lower protrusion. The diameter of the cutterhead was 120 mm and its rotational speed was set at 5637 rpm, which gave a cutting speed of 35.4 m/s. Previous cuts were carried out to level samples before each treatment. As shown in Table 1, eight feed speeds were combined with two cutting depths to obtain four average chip thicknesses of 0.10, 0.14, 0.18, and 0.22 mm according to Eq 1. The 30 boards hence underwent eight planing treatments. Boards planed at 0.5 mm of cutting depth were fed at 8.5, 12, 16, and 20 m/min, which corresponded to wavelengths (or feed per knife) of 1.5, 2.1, 2.8, and 3.5 mm, respectively. Boards planed at 1.0 mm of cutting depth were fed at 6, 9, 11, and 15 m/min, which produced wavelengths of 1.1, 1.6, 2.0, and 2.7 mm, respectively.

The average chip thickness was calculated according to the Eq 1 given by Koch (1964):

$$a_{av} = \frac{f}{n * z}\sqrt{\frac{h}{D}} \tag{1}$$

a_{av} = average chip thickness (mm)

f = feed speed (m/min)

n = rotational speed (rpm)

z = number of knives on cutterhead

h = cutting depth (mm)

D = diameter of cutting circle (mm)

Wood Dust Measurements

Wood dust data were obtained using a DustTrak DRX™ aerosol monitor (model 8534; TSI Incorporated, Shoreview, MN). This light-scattering laser photometer simultaneously measures five size-segregated mass fraction concentrations (mg/m^3): PM_1, $PM_{2.5}$, $PM_{4.0}$, PM_{10}, and Total PM. These fractions include particles with aerodynamic diameter from 0.10 μm and equal or smaller to 1.0, 2.5, 4.0, 10, and 15 μm, respectively. The principle of this device combines both particle cloud (total area of scattered light) and single particle detection to achieve mass fraction measurements. Dust sampling was conducted during the machining treatments.

A dust collector system was developed to capture all particles produced by the machining treatments (Fig 1). The debris was aspirated through a cyclone separator using a vacuum cleaner with strong suction force. The cyclone separator (Dust Deputy®, Oneida) was used to separate coarse material from fine dust by a cyclonic action. As debris enters the vortex, centrifugal force concentrates the particles at the periphery. The cyclone being conical, the debris spirals downward, losing velocity, and separating from the airstream. The finer particles following the airstream were sent to a vacuum cleaner, whereas the larger chips entered to the vortex of air and fell to the bucket bottom. The aerosol monitor device was installed to the pipe which connected the separator and the vacuum cleaner to measure only the fine particles. The monitor device was cleaned and calibrated after every run. The aim of this configuration was to compare the dust emission among machining treatments.

The DustTrak DRX™ monitor can take one measurement per second. Given the level of

Table 1. Cutting parameters used in the present study.

Parameter	Values	
Average chip thickness (mm)	0.10, 0.14, 0.18, and 0.22	
Cutting depth (mm)	0.5	1.0
Feed speed (m/min)	8.5, 12, 16, and 20	6, 9, 11, and 15
Wavelength (mm)	1.5, 2.1, 2.8, and 3.5	1.1, 1.6, 2.0, and 2.7

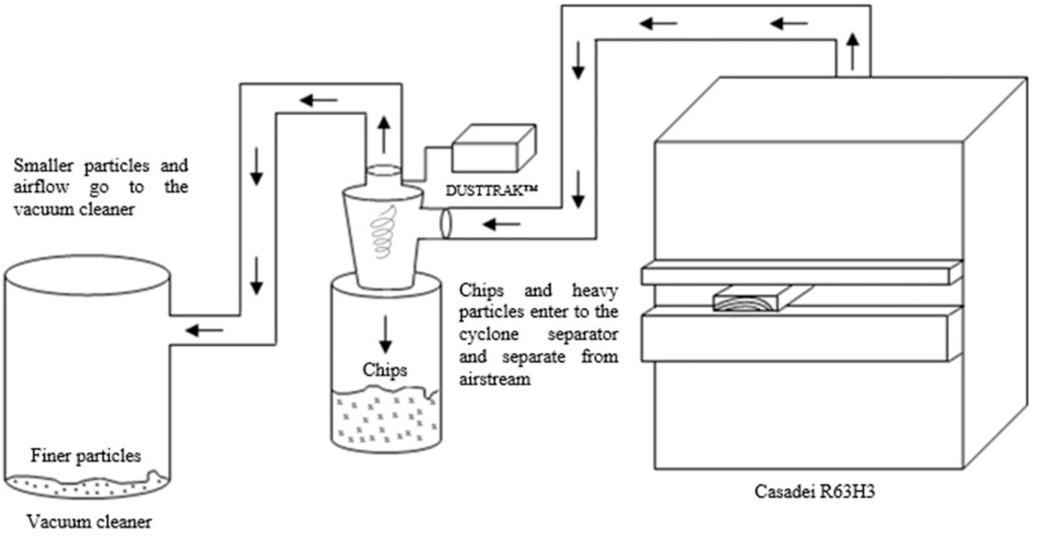

Figure 1. Dust measurement system used during machining treatments.

feed speeds studied, the boards were planed by groups of five pieces each to have an adequate number of points of measurements. The planing length of each of the six groups formed was therefore 4.5 m. The mean mass fraction concentrations were hence measured between 13.5 and 45 s, depending on the feed speed used. Different chip volumes were also obtained because two cutting depths were studied. For this reason, mass fraction concentrations data were adjusted according to a formula proposed by Palmqvist and Gustafsson (1999). Thus, adjusted concentrations indicate the amount of dust produced per unit wood volume instead of the amount produced over a certain period of time. Based on this assumption, the mass fraction concentrations (mg/m^3) were adjusted for the feed speeds and cutting depths studied. The mean value of feed speed and the higher cutting depth (13 m/min and 1 mm, respectively) used in the present study were set up as reference values. The adjusted mass fraction concentration (mg/m^3) was calculated as follows:

$$\text{Adjusted concentration} = A\left(\frac{13}{f} * \frac{1}{h}\right) \quad (2)$$

A = measured mass fraction concentration (mg/m^3)

f = current feed speed (m/min)

h = current cutting depth (mm)

Roughness Measurements

Three-dimensional measurements of surface roughness were obtained with a MicroMeasure profilometry system (Stil, Aix-en-Provence, France). Ten of the 30 boards for each planing treatment were selected to evaluate this property. A surface of 12.5 mm by 15 mm was analyzed per sample by Surface Map 2.4.13 software (Stil, Aix-en-Provence, France). Acquisition frequency and scanning rate were 30 Hz and 3 mm/s, respectively. Measurement steps were 50 and 100 μm in y (longitudinal direction) and x (tangential direction) axes, respectively. Roughness parameters were calculated by Mountain® software, (Digital Surf, Besançon, France), with a cutoff length of 2.5 mm combined with a Robust regression Gaussian filter (ISO 16610-31 2002). The mean surface roughness (S_a) is the arithmetic mean of the absolute values of the profile deviations from the mean line of roughness profile. S_a was determined according to ISO 4287 (ISO 1997). The core roughness depth (S_k) describes the depth of the roughness core profile. S_k was calculated from the Abbot curve according to ISO 13565-2 (ISO 1996).

Statistical Analyses

Experiments were analyzed as a factorial design, with six and ten replicates per treatment, for dust and roughness measurements, respectively. Statistical analyses were done on SAS statistical package, version 9.4, SAS Institute Inc., USA. Dust and roughness data were analyzed as a repeated measures design given that these properties were evaluated on the same specimens for all planing conditions studied. Thus, analyses of variance following the Mixed procedure with the repeated statement were conducted for dust fraction and surface roughness data. Means difference comparison tests were applied to determine significant differences at 5% probability level, when required. Multiple regression analyses were performed with Reg procedure to formulate prediction models for each particle size fraction. Log transformation was applied to the response variables to improve the models and reduce skewness.

RESULTS AND DISCUSSION

Wood Dust Emission

The results of dust emission during helical planing red oak wood are presented in Tables 2 and 3. The ANOVA showed that dust emission was significantly affected by average chip thickness, cutting depth, and the interaction between these two variables. This interaction indicates that the effect of average chip thickness on dust emission depended on the cutting depth studied. Thus, dust emission decreased as chip thickness increased regardless of cutting depth (Table 3). This effect was higher for 1.0 mm of cutting depth compared with 0.5 mm of cutting depth (Fig 2). These results confirm earlier studies undertaken with several wood species and wood products (Palmqvist and Gustafsson 1999; Kos et al 2004; Rautio et al 2007; Fujimoto et al 2011). In this study, changes in average chip thickness were obtained by keeping constant the cutting speed and the number of knives and by changing feed speed and cutting depth. As a result, as feed speed increased, average chip thickness increased resulting in a lower production of fine particles. Inversely, as feed speed decreased, the average chip thickness decreased, which increased the concentration of smaller particles. This inevitably leads to a greater chance of inhaling particles by the woodworkers. To avoid the production of dust during helical planing, high feed speeds should be chosen.

The results also showed that, for a given average chip thickness, the level of dust emission varied according to the cutting depth used. Thus, the highest dust emission was obtained when helical planing at 0.10-mm chip thickness and 1.0-mm cutting depth (Fig 2). Dust emission was reduced by 46% when planing with the same chip thickness but at 0.5-mm cutting depth (Table 3). This difference in dust emission between the two cutting depths was statistically significant. For average chip thicknesses of 0.14 μm and higher, dust emission was statistically similar between the two cutting depths studied (Table 3). Therefore, the effect of cutting depth on dust concentration was only detected for the smaller chip

Table 2. *F* values obtained from the ANOVA for adjusted dust concentrations produced during helical planing red oak wood.

Source of variation	Adjusted concentration				
	$PM_{1.0}$	$PM_{2.5}$	$PM_{4.0}$	PM_{10}	Total PM
Average chip thickness (a_{av})	156**	160**	158**	146**	134**
Cutting depth (h)	23**	25**	30**	35**	36**
$a_{av} \times h$	17**	18*	20**	23**	22**

ANOVA, analysis of variance.
*,** Statistically significant at the 5 and 1% probability levels, respectively.

Table 3. Mean values of adjusted concentrations produced during helical planing red oak wood for each particle size fraction.

Cutting depth (mm)	Average chip thickness (mm)	Feed speed (m/min)	Wavelength (mm)	Particle size fraction (adjusted concentration) (mg/m^3)				
				$PM_{1.0}$	$PM_{2.5}$	$PM_{4.0}$	PM_{10}	Total PM
0.5	0.10	8.5	1.5	15^{*e} (1)	16^{d} (1)	16^{d} (1)	17^{d} (1)	18^{d} (2)
	0.14	12	2.1	10^{d} (1)	10^{c} (1)	10^{c} (1)	11^{c} (1)	11^{c} (2)
	0.18	16	2.8	6^{ab} (1)	6^{ab} (1)	7^{ab} (1)	7^{ab} (1)	7^{ab} (2)
	0.22	20	3.5	5^{a} (1)	5^{a} (1)	5^{a} (1)	6^{a} (1)	6^{a} (2)
1.0	0.10	6	1.1	24^{f} (1)	25^{e} (1)	28^{e} (1)	31^{e} (1)	32^{e} (2)
	0.14	9	1.6	10^{cd} (1)	11^{c} (1)	11^{c} (1)	11^{c} (1)	11^{c} (2)
	0.18	11	2.0	8^{bc} (1)	8^{bc} (1)	8^{bc} (1)	9^{bc} (1)	9^{bc} (2)
	0.22	15	2.7	5^{a} (1)	5^{a} (1)	5^{a} (1)	6^{a} (1)	6^{a} (2)

*Values are means of 6 replicates (standard error of the mean in parentheses). Means within a column followed by the same letter are not significantly different at the 5% probability level. Where: $PM_{1.0}$ = particles with a diameter from 0.10 μm and equal or smaller than 1.0 μm, $PM_{2.5}$ = particles with a diameter equal or smaller than 2.5 μm, $PM_{4.0}$ = particles with a diameter equal or smaller than 4 μm, PM_{10} = particles equal or smaller than 10 μm, and Total PM = total particulate matter, particles with a diameter between 0.10 and 15 μm.

thickness. This result could be interpreted as contrary to findings of Palmqvist and Gustafsson (1999) and Rautio et al (2007), which reported that the same chip thickness produced the same fine dust mass regardless of how this chip thickness was obtained. However, in those prior studies, changes in the average chip thickness were obtained by varying the feed speed and rotational speed. The cutting depth in these cases was kept constant. Even though in the present study dust concentration was adjusted by the volume of chips produced (at equal chip volume), results showed that dust emission will be affected by the cutting depth for small chip thicknesses.

The means' comparison tests showed that the lowest dust emission was obtained from 0.18 mm and higher average chip thicknesses for 0.5-mm cutting depth and for 0.22-mm average chip thickness for 1.0-mm cutting depth, respectively (Table 3). Lower values

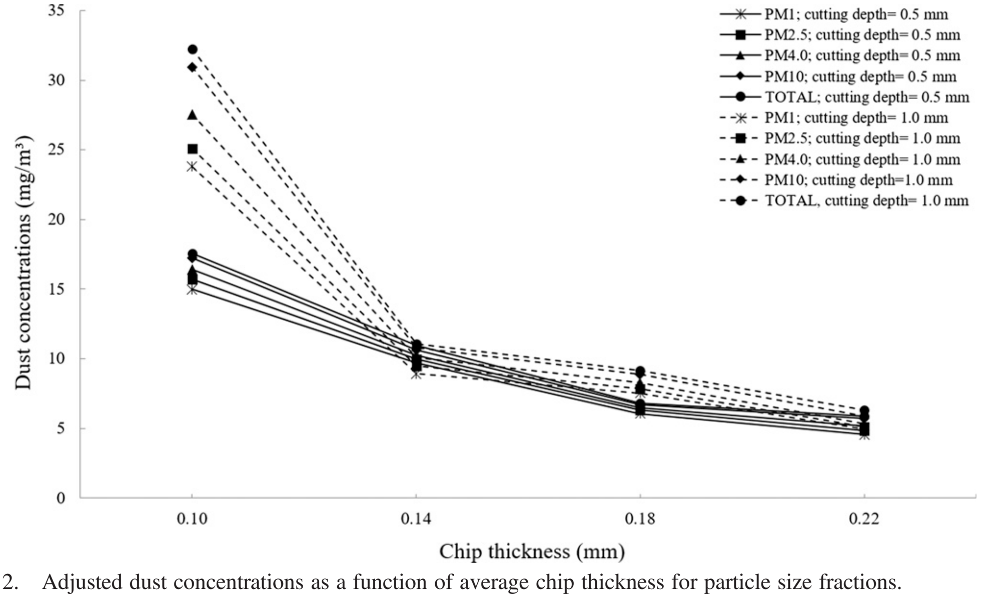

Figure 2. Adjusted dust concentrations as a function of average chip thickness for particle size fractions.

of chip thickness increased significantly dust emission. Ratnasingam et al (2009) found that an average chip thickness between 0.10 and 0.15 mm minimized dust emission during routing rubberwood. Higher values of average chip thickness were not considered in that study. Palmqvist and Gustafsson (1999) also reported that dust emissions increase dramatically at average thicknesses below 0.10 mm. Rautio et al (2007) suggested values greater than 0.05 mm to reduce the amount of dust. However, experiments in that case implicated machining of medium density fiberboards, which produced 30 times more airborne dust compared with solid pine.

Dust Emission Models

The relationship between dust generated during helical planing red oak wood and the two machining parameters studied were modeled using multiple linear regression analysis. The models predicted dust emissions for each particle size fraction from average chip thickness and cutting depth (Table 4). Log-linear models explained between 82% and 85% of the variation in the ln-transformed particle size fractions $PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$, PM_{10}, and Total PM. The regression coefficients of the models are also at log scale. The model is however presented under exponential form to obtain the results directly in the original scale as shown in Table 4. Furthermore, the Eq 3 can be used to convert adjusted concentration to mass fraction concentration directly measured with an aerosol monitor without compensation for the effect of chip volume on dust generation.

Equation to convert adjusted dust concentration to mass fraction concentration:

$$[\,]\ \frac{\text{mg}}{\text{m}^3} = \frac{AC_{PM_n}}{\frac{13}{s} * \frac{1}{h}} \qquad (3)$$

AC_{PM_n} = adjusted concentration value for a given particle size fraction (mg/m^3)

s = feed speed (m/min)

h = cutting depth (mm)

Surface Roughness

Changes in cutting depth and average chip thickness did not affect the mean surface roughness (S_a) of helical planed boards. Previous works have reported that measurements of S_a alone do not adequately evaluate surface roughness (Gurău 2013). Thus, the core roughness depth (S_k) was more sensitive and resulted significantly affected by the average chip thickness. The highest values of S_k were found at the highest average chip thickness for both cutting depths (Table 5). Previous works have also reported that surface roughness increases as feed speed increases during planing oak wood (Škaljić et al 2009; Ugulino and Hernández 2016). Iskra and Hernández (2012) reported that the parallel and normal force components increase as chip thickness increases. It is known that higher cutting forces can increase the risk of distortion and weakness of wood tissues at surface (de Moura and Hernández 2006a; Iskra and Hernández 2012). The vibration produced during helical planing will also be increased as

Table 4. Predictive models for adjusted dust concentrations for each dust size fraction as a function of cutting depth and average chip thickness. Results of regression analysis between ln-transformed particle size fractions.

		Coefficients		
Dust fraction	Intercept	Cutting depth (mm)	Average chip thickness (mm)	Adjusted R^2
$AC_{PM_{1.0}}$ =	e [(3.7	+ 0.3 (h)	−11.3 (a_{av}))]	0.84*
$AC_{PM_{2.5}}$ =	e [(3.8	+ 0.3 (h)	−11.3 (a_{av}))]	0.85
$AC_{PM_{4.0}}$ =	e [(3.8	+ 0.4 (h)	−11.4 (a_{av}))]	0.84
$AC_{PM_{10}}$ =	e [(3.8	+ 0.4 (h)	−11.3 (a_{av}))]	0.83
AC_{Total} =	e [(3.8	+ 0.5 (h)	−11.1 (a_{av}))]	0.82

*All coefficients are significant at the 5% probability level.

Table 5. Roughness values for red oak surfaces prepared by helical planing.

Cutting depth (mm)	Average chip thickness (mm)	Feed speed (m/min)	Wavelength (mm)	Roughness parameters (μm)	
				S_a	S_k
0.5	0.10	8.5	1.5	23*[a] (4)	10[a] (2)
	0.14	12	2.1	21[a] (4)	10[a] (2)
	0.18	16	2.8	23[a] (4)	9[a] (2)
	0.22	20	3.5	24[a] (4)	16[b] (2)
1.0	0.10	6	1.1	27[a] (4)	8[a] (2)
	0.14	9	1.6	20[a] (4)	9[a] (2)
	0.18	11	2.0	20[a] (4)	8[a] (2)
	0.22	15	2.7	26[a] (4)	13[b] (2)

*Values are means of 10 replicates (standard error of the mean in parentheses). Means within a column followed by the same letter are not significantly different at the 5% probability level, where S_a = mean surface roughness and S_k = core roughness depth.

cutting forces increase. Thus, the results show that S_k was statistically similar from 0.10 to 0.18 μm chip thickness for both cutting depths (Table 5). At 0.22 μm of cutting depth, S_k increased significantly producing on average surfaces 60% rougher than the previous ones.

This increase in S_k occurs at equal chip thickness (0.22 μm) for the two studied cutting depths. However, this chip thickness will be reached at higher feed speed for 0.5 mm of cutting depth than for 1 mm of cutting depth. Therefore, taking into account productivity and surface roughness, it should be recommended to work at 0.5-mm cutting depth and 16 m/min of feed speed for helical planing red oak wood. As indicated earlier, this cutting condition will also minimize the production of adjusted dust concentration.

CONCLUSION

Airborne dust and surface roughness produced during helical planing red oak wood were affected by the studied cutting parameters. Dust emission decreased and core roughness depth (S_k) increased as average chip thickness increased. Dust emission also decreased as cutting depth decreased but for small average chip thickness. Knowledge of these relationships helps to minimize dust emission and consequently the exposure to respirable wood dust. Regression models for estimating dust emission for each particle size fraction as a function of average chip thickness and cutting depth were developed. The best helical planing condition was obtained when using 0.5-mm cutting depth, 0.18-mm average chip thickness, and 16 m/min feed speed. This condition was the fastest feed speed allowable to obtain the best surface quality while minimizing dust production.

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