Cutting Conditions and Tool Wear when Machining Wood-Based Materials

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The article deals with data in the cutting process of wood-based materials. The cutting process influences the shape and dimensions of a cutting edge. The experiments were focused on monitoring the changes of the cutting edge in machining of particle board and the influence of cutting speed on the tool wear. Cutting tests were performed during milling at cutting rates in the range 7.95 to 17.9 m/s (477 to 1074 m/min), a depth of cut of 9.5 mm, and a tooth feed of 0.05 mm. The wear process of cutting wedge during particle board milling is characterized by a decrease in the cutting edge of insert blades. The comparative digital dial gauge was used for measurement of the cutting wedge recession. The course of the wear of wood based materials exhibited similarity in graphical representation with abrasive material cutting. The resulting dependency may be used for selection of the most suitable cutting conditions according to operator requirements.

Keywords: Machining; Wood; Tool; Wear; Dulling; Cutting conditions

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INTRODUCTON

Wood is a porous and fibrous structural tissue found in the stems and roots of trees and other woody plants. It is an organic material, a natural composite of cellulose fibers, which are strong in tension and embedded in a matrix of lignin that resists compression. Wood is the one of few materials that are renewable (Kučerová *et al.* 2016). Unfortunately, wood is a relatively low-durability material and requires special care to assure a long-term service life. For that reason, modified or surface-coated wood-based materials are also widely used. To a certain extent, such wood-based materials preserve the good properties of wood and mitigate against some of its unfavorable properties (Kvietkova *et al.* 2015a,b,c; Gaff *et al.* 2016; Sedlecký and Sarvašová Kvietková 2017).

Mechanical and physical properties are important factors in wood processing. Agglomerated materials are made from wood or other lignocellulosic particles.

Particle board is a term for material made of wood particles that are produced in variety of shapes and sizes. Wood chips are bonded using synthetic glue, high pressure, and increased temperature. For interior use, these materials often need to be veneered, laminated, or folded to improve their appearance. The material is most widely used and most manufactured agglomerated material in the woodworking industry (Thoemen *et al.* 2010).

During the milling process, cutting inserts within the rotating tool separate the workpiece material in the form of chips. The feed rate is limited by size and type of cutting tool perpendicular to the machined part. The cutting process is intermittent, and the cutter teeth alternately cut short chips of varying thickness. Wood-based materials are milled in all directions, but most often along the direction of wood fibres. The direction of rotation is usually chosen to be conventional, *i.e.* against the feed rate direction. With respect to the position of the axis of rotation and the surfaces created by the cutting edges, the milling is divided into two types: either the cylindrical-tool axis is parallel with the workpiece surface, or the front-axis of the tool is perpendicular to the workpiece surface.

The milling process is monitored using the tool life. Tool life is the period during which the blade is in working condition in the machining process. It is the time when the tool is working, from sharpening to dulling. When machining the metal, abrasion wear process is observed on the clearance face of cutting edge and is referred to as VB flank wear. Figure 1 shows this process on the wear curve. The individual phases are: I - initial rapid wear, II - linear wear, and III - final unstable course. The practical wear measurement uses the value of critical wear VB in the linear phase II; this selection is due to the accuracy of the reading value (Shaw 2005; Csanády and Magoss 2012).

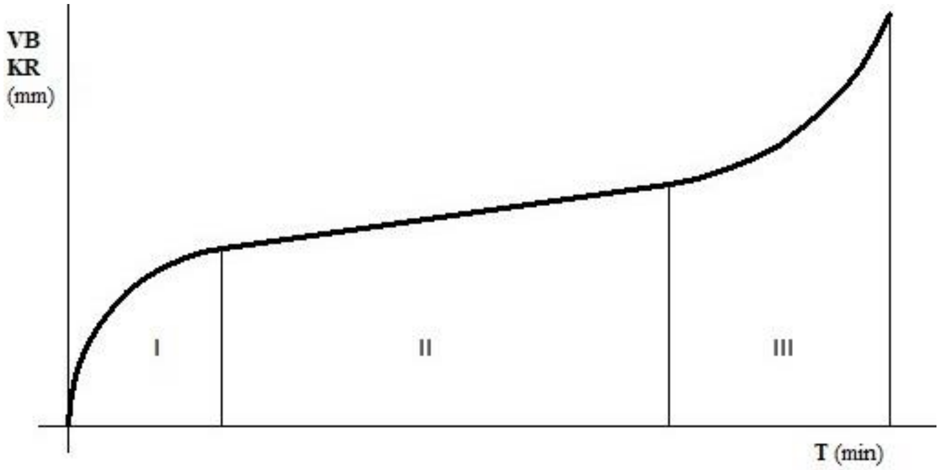

Fig. 1. Graphical representation of the dependence VB or KR = fn (*T*) in metal cutting

The cutting edge is formed by the intersection of two surfaces - the face plane (rake angle γ) and the clearance plane (clearance angle α). Darmawan *et al.* (2001, 2012) studied wear process on the clearance face influenced by different wood based materials and materials of cutting tool edge. During machining wood based materials without abrasives the wear on the tool edge recession is monitored depending on time (Šebelová and Chladil 2013). This type of wear is called nose wear (Shaw 2005; Mazan *et al*. 2017), and its size corresponds to radial wear KR (see Fig. 2).

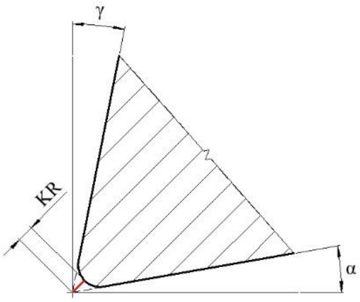

Fig. 2. The nose wear type of tool wear

In this study, a wood-based material – laminated particle board – was used to experimentally examine the influence of cutting conditions on tool wear. Cylindrical milling was used to test properties of the tool material in the cutting process, and a two-tooth right-hand milling cutter was applied. The tool dulling process was monitored because this affects cutting tool lifetime and thus also the machining efficiency. The Taylor’s time *vs*. cutting speed formula was used for evaluation (Shaw 2005).

EXPERIMENTAL

Workpiece Material

Laminated particle board was used as the representative of wood-based materials laminated with beech. The supplier of the laminated particle board (045 BS beech Westfalen 18mm thick) was INTEREXPO Brno Ltd, Czech Republic. The board volume weight was 600 to 750 kg.m^{-3} and moisture 14.2% determined according to EN 323 (1993).

Cutting Tool

The two-teeth clockwise milling cutter FRSTHW 19x30x12z2 (Aparathea Ltd., Brno, Czech Republic) with diameter D of 19 mm was used for experiments. Cutter inserts made of sintered carbide K10, HW 29.5x12x1.5 4S T04F were used at the cutter (Fig. 3). The cutting tool geometry: rake angle γ of 15° and clearance angle α of 20°.

Fig. 3. Milling cutter HW 19 x 30

Sintered carbide (SC) inserts were clamped into the milling cutter and secured with a bolt. The carbide inserts were identified by a letter with the appropriate symbol-letter to distinguish use in the machining of individual samples and for the uniqueness of the individual measurements. The number denoted a particular cutting inserts had the lower letter case a / b to distinguish the blade side. Cutting inserts marked U1 to U4 Fig. 4 were used for cutting the laminated particle board.

Fig. 4. SC cutting inserts HW 29.5x12x1.5 4S T04F

Machine Tool

The selected materials were machined on a three axis milling CNC machine SCM Tech 99 (Rimini, Italy) with the following parameters: working dimensions X, 3119 mm, Y, 1012 mm, Z, 100 mm; motor power, 6.6 kW, and maximum rotational speed of 1800 rpm. The two-teeth clockwise milling cutter was clamped in the milling CNC machine.

Methods

Cutting conditions

A climb milling was selected for machining. The range of minimum 4000 rpm and a maximum 18000 rpm were determined for a constant feed on the tooth ($f_z = 0.05$ mm) and a constant width of cut $a_p = 18$ mm (material thickness). Cutting and feed rate values are based on the relationship between tooth feed value, cutting speed, tool speed, and cutter diameter. All variables are defined in Table 1. The cutting speed (v_c) was determined by Eqs. 1 and 2.

$$v_c = \frac{\pi \cdot D \cdot n}{10^3} \quad \left[m \cdot min^{-1}\right] \tag{1}$$

$$n = \frac{10^3 . v_c}{\pi . D} \quad [rpm] \tag{2}$$

The feed rate v_f was calculated by Eq. 3.

$$v_f = f_z \cdot z \cdot n \quad \left[mm \cdot min^{-1}\right] \tag{3}$$

Table 1. Process Conditions of Cutting for Experiments

Parameter	Value
Tool diameter D (mm)	19
Feed per tooth f_z (mm)	0.05
Number of teeth z	2
Depth of cut h_{max} (mm)	9.5
Speed range n used (rpm)	8000, 12000, 15000, 18000
Feed rates v_f (mm · min^{-1})	800, 1200, 1500, 1800
Corresponding cutting speeds v_c (m · min^{-1})	477, 716, 895, 1074
Basic length of cut L (mm)	700

Tool wear

The tool life of the cutting edge is most affected by the cutting speed v_c. Experimental determination of the tool life dependence on the cutting speed, *i.e.*, $T = \text{fn}\,(v_c)$, was carried out using several cutting speeds. It was necessary to ensure that other working conditions were constant. The wear on the tool was represented by the wear curves for individual cutting speeds in the diagram KR = fn (T) for radial wear. Measurement of flank wear VB mainly used in metal cutting could not be used due to the difficulty measuring any changes during the experiments.

To measure the radial wear of the KR tool, which is defined by the dependence KR = fn (T), it was necessary to calculate the time according to the following equation,

$$T = \frac{L}{v_f} \quad \left[mm \cdot min^{-1}\right] \tag{4}$$

where T is the cutting time (min), L=700 is the length of workpiece (mm), and v_f is the feed rate (mm · min^{-1}). The tool wear criterion was determined as KR = 10 µm.

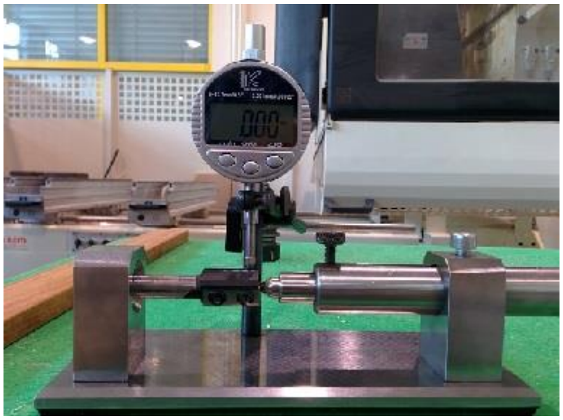

Fig. 5. The comparison measurement instrument

Measuring equipment

To measure the tool wear, a digital dial gauge (KINEX 0-12.7 / 0.001, Prague, Czech Republic) was fixed on a measurement jig that was developed for the experiments see Fig. 5. The instrument measures deviations from the set dimension. First, it was necessary to calibrate the instrument according to the new tool inserts. The device used had measurement accuracy of 1 µm and maximum touch stroke of 12.7 mm.

Evaluation of measured values

Minitab® 15 statistical software (State College, PA, USA) was used to evaluate the measured values from experiments.

RESULTS AND DISCUSSION

Radial Wear *vs*. Time

The radial wear KR of the cutting tool is time dependent.

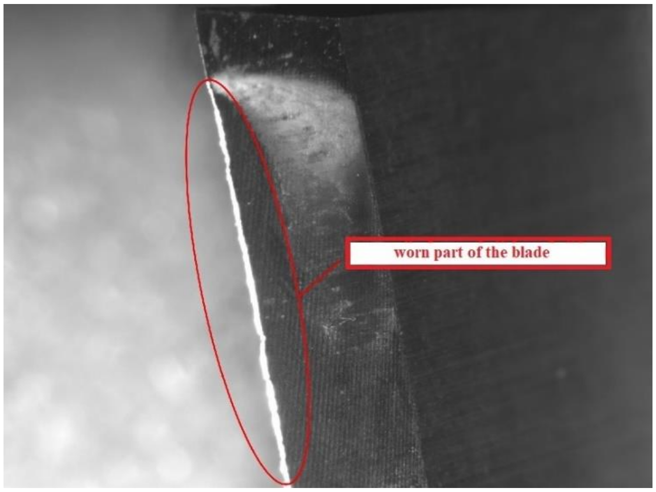

Fig. 6. Tool wear of a cutting insert (red colored mark)

At time intervals that are given by the time of cutting, KR wear measurement has been performed. The results are further elaborated in time dependence graphs. The tool wear of inserts is shown using red colored mark in Fig. 6.

The resulting dependencies of the tool wear KR = fn (*T*), taken from the linear part wear that are highlighted in gray in tables, are attached to the tables of measurement in Figs. 7 to 10.

Table 2. Measurement of Tool Wear *vs*. Time, Inserts U1a / U2a, Speed v_{c1} = 477 m/min

Measurement No.	Time (min)	Length of cut (mm)	Wear of U1a (µm)	Wear of U2a (µm)	Average wear (µm)
1	**0**	0	0	0	**0**
2	**1.75**	1400	2	1	**1.5**
3	**3.50**	1400	3	3	**3.0**
4	**5.25**	1400	4	4	**4.0**
5	**10.50**	4200	5	5	**5.0**
6	**19.25**	7000	6	6	**6.0**
7	**36.75**	14000	8	7	**7.5**
8	**54.25**	14000	9	9	**9.0**
9	**71.75**	14000	11	11	**11.0**
10	**89.25**	14000	13	12	**12.5**
11	**106.75**	14000	15	14	**14.5**

Table 3. Measurement of Tool Wear *vs*. Time, Inserts U1b / U2b, Speed v_{c2} = 716 m/min.

Measurement No.	Time (min)	Length of cut (mm)	Wear of U1b (µm)	Wear of U2b (µm)	Average wear (µm)
1	**0**	0	0	0	**0**
2	**1.17**	1400	2	1	**1.5**
3	**2.34**	1400	3	3	**3.0**
4	**5.84**	4200	5	4	**4.5**
5	**9.34**	4200	7	6	**6.5**
6	**15.17**	7000	9	8	**8.5**
7	**21.00**	7000	10	9	**9.5**
8	**32.67**	14000	11	10	**10.5**
9	**44.34**	14000	11	11	**11.0**
10	**56.01**	14000	12	11	**11.5**
11	**67.68**	14000	13	13	**13.0**
12	**79.35**	14000	15	14	**14.5**

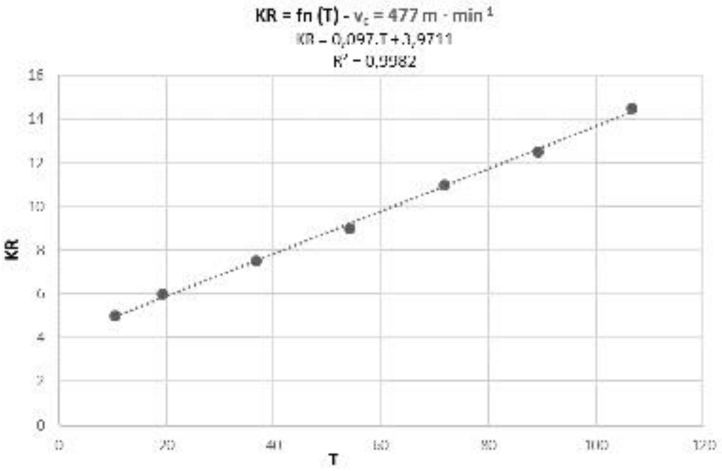

Fig. 7. The regression of linear wear for v_{c1} = 477 m/min, KR [µm] and *T* [min]

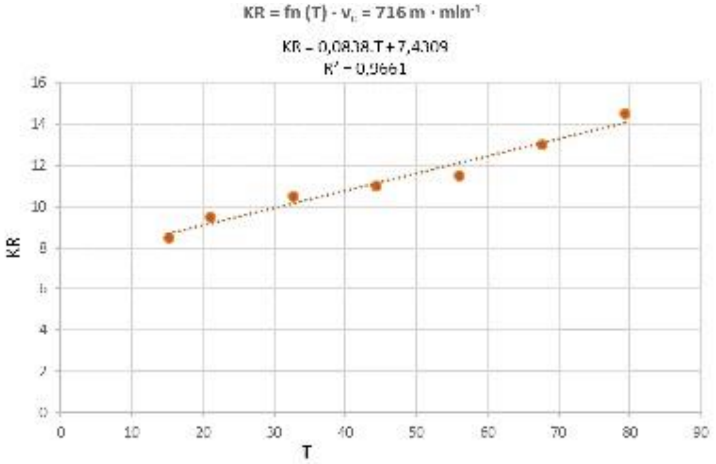

Fig. 8. The regression of linear wear for v_{c2} = 716 m/min, KR [µm] and *T* [min]

Table 4. Measurement of Tool Wear *vs*. Time, Inserts U3a / U4a, Speed v_{c3} = 895 m/min

Measurement No.	Time (min)	Length of cut (mm)	Wear of U3a (µm)	Wear of U4a (µm)	Average wear (µm)
1	**0**	0	0	0	**0**
2	**0.78**	700	2	2	**2.0**
3	**1.56**	700	3	3	**3.0**
4	**2.35**	700	4	4	**4.0**
5	**3.91**	1400	6	5	**5.5**
6	**5.48**	1400	7	6	**6.5**
7	**10.17**	4200	9	8	**8.5**
8	**14.86**	4200	9	9	**9.0**
9	**22.68**	7000	11	10	**10.5**
10	**38.32**	14000	12	12	**12.0**
11	**53.97**	14000	14	14	**14.0**
12	**69.61**	14000	16	16	**16.0**

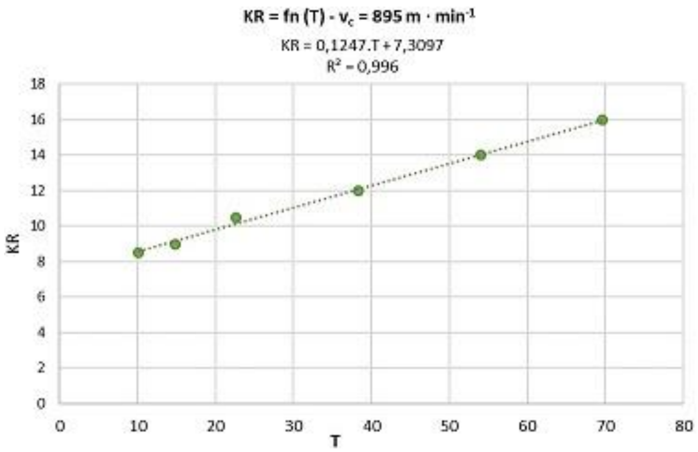

Fig. 9. The regression of linear wear for v_{c3} = 895 m/min, KR [µm] and *T* [min]

Table 5. Measurement of Tool Wear *vs*. Time, Inserts U3b / U4b, Speed v_{c4} = 1074 m/min

Measurement No.	Time (min)	Length of cut (mm)	Wear of U3b (µm)	Wear of U4b (µm)	Average wear (µm)
1	**0**	0	0	0	**0**
2	**0.39**	700	2	2	**2.0**
3	**0.78**	700	3	3	**3.0**
4	**1.17**	700	3	3	**3.0**
5	**1.56**	700	5	4	**4.5**
6	**2.33**	1400	6	5	**5.5**
7	**3.11**	1400	8	8	**8.0**
8	**5.45**	4200	9	9	**9.0**
9	**9.33**	7000	10	9	**9.5**
10	**13.22**	7000	11	11	**11.0**
11	**21.00**	14000	12	12	**12.0**
12	**28.78**	14000	14	13	**13.5**
13	**36.56**	14000	15	15	**15.0**

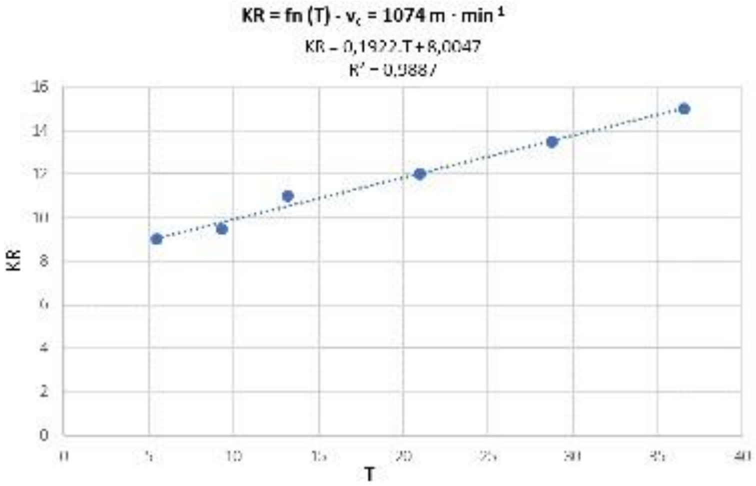

Fig. 10. The regression of linear wear for v_{c4} = 1074 m/min, KR [µm] and *T* [min]

The relationship between tool life *T* and cutting speed v_c is as follows:

$$\boldsymbol{T \,.\, v_c^{m} = const.} \qquad (5)$$

Here, the Taylor's equation replaces the exponent $\boldsymbol{m = 1/n}$. A wear rate of 10 μm from the original value of the cutting edge was determined as a criterion to state the tool life for that rate. To determine the dependence of tool life on cutting speeds, the T and v_c values for the tool wear criterion were used into graphic representation log (T) = fn (log v_c) (see Table 6). The statistical method of linear regression was then applied for solution. Confidence intervals (95%) of the measured data T = fn (v_c) graphs for laminate particle board materials were processed. Results are shown in Fig. 11.

Table 6. Cutting Speeds and Corresponding Tool Life T1-T4 for KR = 10 μm

v_{c1} = **477** m · min^{-1}	v_{c2} = **716** m · min^{-1}	v_{c3} = **895** m · min^{-1}	v_{c4} = **1074** m · min^{-1}
KR = 0,097.T + 3,9711	KR = 0,0838.T + 7,4309	KR = 0,1247.T + 7,3097	KR = 0,1922.T + 8,0047
T_1 = **62.2** min	T_2 = **30.7** min	T_3 = **21.6** min	T_4 = **10.4** min

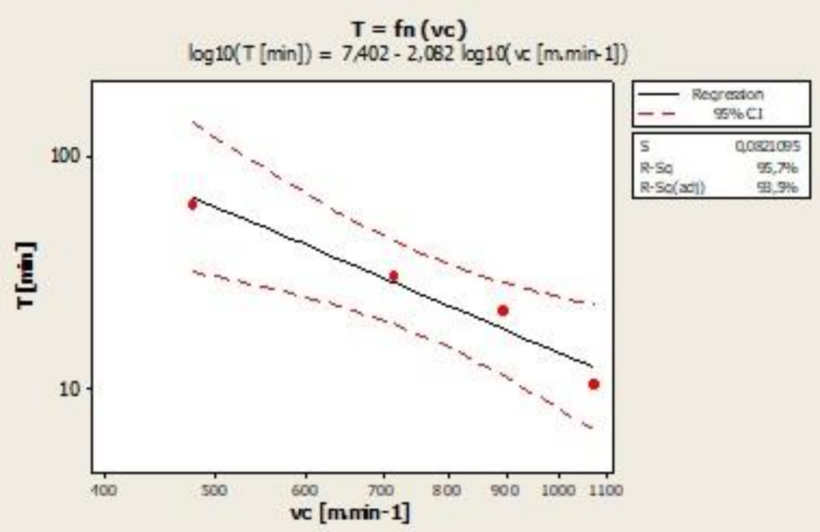

Fig. 11. Regression of T = fn (v_c) with a confidence interval 95%

Equation 5 corresponding to the function from the graphic representation in Fig. 11 is then in final formula (Eq. 6).

$$\boldsymbol{T\, v_c^{\,2.082} = 252.35 \times 10^5} \quad \text{or} \quad \boldsymbol{v_c\; T^{\,0.48} = 3590.7} \qquad (6)$$

CONCLUSIONS

1. The wear mechanism of the particle board is different from the wear mechanism with abrasive particles that are characteristic of metals with abrasive particles. Darmawan *at al.* (2001, 2012) used the measurement of the wear on the clearance face.

2. In the article, the comparative digital gauge used the measurement of radial wear KR that corresponds to cutting tool recession been used during the experiments. The course of the wear of wood-based materials exhibited similarity of the graphical representation with abrasive material cutting.
3. The final dependence $T = \text{fn}(v_c)$ for machining the laminated particle board to select the proper cutting rate for a given tool life was determined. The final equation may be used for calculation of cutting rate/tool life according to operator demands.
4. The criterion for determining tool life been selected in the linear part of wear curve to get proper and accurate results with the use of linear regression
5. The experiments were evaluated using regression analysis.

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REFERENCES CITED

Csanády, E., and Magoss, E. (2012). "Mechanics of Wood Machining" (2^{nd} Ed.), *Springer*, New York, NY.

Darmawan, W., Tanaka C., Usuki H., and Ohtani T. (2001). "Performance of coated carbide tools in turning wood-based materials: Effect of cutting speeds and coating materials on the wear characteristics of coated carbide tools in turning wood-chip cement board," *Wood Science* 47(5), 342-349.

Darmawan, W., Rahayu, I., Nandika, D., and Marchal, R. (2012). "The importance of extractives and abrasives in wood materials on the wearing of wood cutting tools," *BioResources* 7(4), 4715-4729. DOI: 10.15376/biores.11.4.4715-4729

Gaff, M., Sarvašová-Kvietková, M., Gašparík, M., and Slávik, M. (2016). "Dependence of roughness change and crack formation on parameters of wood surface embossing" *Wood Research* 61(1), 163-174.

Kučerová, V., Lagaňa, R., Výbohová, E., and Hýrošová, T. (2016). "The effect of chemical changes during heat treatment on the color and mechanical properties of fir wood," *BioResources* 11(4), 9079-9094. DOI: 10.15376/biores.11.4. 9079-9094

Kvietková, M., Gaff, M., and Gašparík, M. (2015a). "Effect of thermal treatment on surface quality of beech wood after plane milling," *BioResources* 10(3), 4226-4238. DOI: 10.15376/biores.10.3. 4226-4238

Kvietková, M., Gaff, M., Gašparík, M., Kaplan, L., and Barcík, Š. (2015b). "Surface quality of milled birch wood after thermal treatment at various temperatures," *BioResources* 10(4), 6512-6521. DOI: 10.15376/biores.10.4. 6512-6521

Kvietková, M., Gaff, M., Gašparík, M., Kminiak, R., and Kris, A. (2015c). "Effect of number of saw blade teeth on noise level and wear of blade edges during cutting of wood," *BioResources* 10(1), 1657-1666. DOI: 10.15376/biores.10.1.1657-1666

Mazáň, A., Vančo, M., and Barcík, S. (2017). "Influence of technological parameters on tool durability during machining of juvenile wood," *BioResources* 12(2), 2367-2378. DOI: 10.15376/biores.12.2. 2367-2378

Šebelová, E. and Chladil, J. (2013). "Tool wear and machinability of wood-based materials during machining process," *Manufacturing Technology* 13(2), 231-236.

Sedlecký, M., and Sarvašová Kvietková, M. (2017). "Surface waviness of medium-density fibreboard (MDF) and edge-glued panel EGP after edge milling," *Wood Research* 62(3), 459-470.

Shaw, M. C. (2005). "Metal Cutting Principles" (2nd Ed.), *Oxford University Press*, Oxford, UK.

Thoemen, H., Irle, M., and Sernek, M. (2010). *Wood-based Panels - An Introduction for Specialists*, Brunel University Press, London.

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