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MACHINABILITY CHARACTERIZATION OF SOLID WOOD WITH SCRATCHING AND DRILLING TECHNIQUES

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ABSTRACT

This paper describes the characterization of four wood species (alder, oak, jatoba and obeche) with regards to their machinability, i.e. susceptibility to mechanical processing expressed by different machinability indicators. Three types of tests were performed. Drilling tests were conducted on a computer numerical control (CNC) working center as well as on a conventional vertical drilling machine. Both machines were fully instrumented with transducers to continuously measure the torque and the thrust force while drilling. Scratching tests were performed on an instrumented shaper, allowing continuous measurement of the normal and tangential components of the total force applied on a cutter while cutting. This resulted in correlations between particular machinability indicators that were estimated with usage of different measurement benches. Moreover, machinability indicators obtained in this way were compared to the mechanical properties of the wood species. Especially strong correlations were obtained with density or strength in static bending. Those alternative techniques were to some extent coincidental. Particularly, similar results occurred with assessments on CNC machine indicators (torque and thrust force) and friction coefficients ($MI_{\varepsilon\text{-drilling}}$) during drilling on a conventional drilling machine or indicator C2. The necessity of some improvements in fitting the geometry of an elementary cutter regards to specific properties of solid wood proved in described below experiments should result in higher reliability and usefulness of testing method.

KEYWORDS: Machinability, drilling, scratching, wood.

INTRODUCTION

Material engineers need simple, fast, and cheap methods to characterize the properties of different types of materials (stones, mortars, concrete and wood) regards to their machinability. The machinability of those materials may be perceived as susceptibility to mechanical processing and can vary greatly. This knowledge is especially useful for the development of new innovative materials. In literature, there are proposed different procedures of machinability assessment. Thus, the question posed is what criterion should be assumed to obtain reliable and applicable results?

According to Jemielniak (1998), the most relevant machinability criteria are the tool life, the quality of the machined surface, the cutting resistance or the shape and the dimensions of the chips. Regards to different kind of machining, other machinability indicators play crucial role. Unfortunately, any discussion that concerns of tool wear must consider multi-component nature of both the work and tool materials (Klamecki 1979).

Thus, preliminary milling indicators based on tool life seems to be the most significant whereas in case of finishing milling the most important factor is perceived as machining quality.

For drilling process with drills of small diameter, the cutting forces are assumed as very relevant machinability criterion because of the danger connected with exceeding of critical value and in consequence the breakage of drill bit (Podziewski et al. 2012).

For a long time, methods based on the cutting resistance (Miernik 2000), can be assumed as fast and low in material consumption. These methods are a good way of comparing different materials and importantly, the methods on cutting resistance indirectly have influences on tool life due to the increase of edge temperature. However, in case of solid wood it is not to omitted influence of relationships between grain orientation, depth of cut, cutting mode (up and down milling) and cutting forces that described (Goli et al. 2010). Especially, some issue can make relative grain orientation affected the force angle.

According to Teng et al. (2014), the machinability regards to drilling of given materials can be analyzed directly where the value of thrust force and torque are taken into account. In this research two discs made of different kinds of medium-density fiberboards (MDF) boards were subjected to turning. Lin et al. (2006) investigated machinability of MDF too. Above mentioned authors focused on quality of machined surface assuming relatively low cutting speed. There were pointed out that density of material have influence on machinability indicators concerning topography of machined surface.

Comprehensive analysis of machinability indicators based on drilling process showed Podziewski et al. (2018). Moreover, this work encompasses huge variety of wood based materials.

Pohl and Wołpiuk (2010) and Wilkowski et al. (2013a) analysed the machinability of wood-plastic composites (WPC) with varied content of polypropylene or polyethylene expressed as specific cutting resistance. The same indicator was used by Wilkowski et al. (2011) to estimate the machinability of hard fiberboard with and without lignin as a binder. Whereas Wieloch and Hofmann (2001) assessed the proper cutting work expressed in J.m-3 for five wood species (pine, poplar, birch, beech and oak), MDF board, chipboard, and five kinds of acrylic conglomerates used in furniture finishing, Wilkowski et al. (2013b) assumed a very low time consuming method of machinability testing during sawing, where the time of the saw passing at the grooving of basic wood-based materials, such as plywood, chipboard, MDF board, or OSB, was registered.

As was mentioned above, an assessment of machinability properties can be made according to cutting resistance during different kinds of technological processes, such as sawing, drilling, or milling. Standard ASTM D-1666-87 (2004) predicts the variety of machining to estimate the machinability of wood. These kinds of machining were applied by Malkocoglu and Ozdemir (2006). Besides drilling, milling, planing, sanding, turning, or chiseling was also performed. However, this method is based on the visual assessment of the wood surface related to a five-grade scale, where after taking into account appropriate wage and number of defects, particular levels are attributed to the work samples: 1 – excellent or defect free, 2 – good, 3 – fair, 4 – poor, and 5 – very poor.

The machinability indicators based on visual grading and three dimensional surface reconstructions were applied by Sandak et al. (2017) in case of analysis of different minor wood species subjected to modification with thermo-vacuum technology. Above mentioned methods turned out effective and reliable.

Some alternative for above mentioned standard can be perceived approach proposed by Goli and Sandak (2016) where obtained overall quantification of roughness parameters along the whole range of grain orientation.

Possible, but untypical, solution proposed by Robinson et al. (2007) for dealing with this problem is that the test consists of merging knife to the depth of 0.635 cm into wood and comparing the indispensable force.

As revealed from above review the wood based materials' machinability indicator are used depending on different technological processes. There is no universal indicator that would comprehensively describe the wood machinability. Additionally, this area constitutes difficulties because of heterogeneity of wood species with varying physical-mechanical properties, including susceptibility to machining. Even, within one wood species there exists huge variety of anatomy structures and in consequence its properties. Thus, steady looking for fast and reliable methods of wood machinability assessment fitted to industry conditions are vital.

The aim of this research involves the relationships between some of machinability indicators assessed for chosen four wood species, so that it would be as strong as possible correlated with different physical and mechanical properties of wood.

MATERIAL AND METHODS

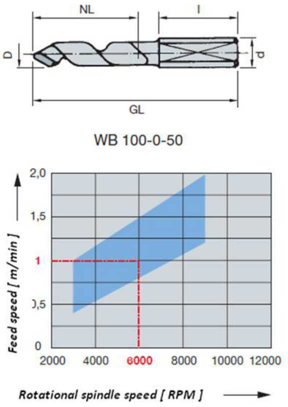
Four groups of materials (wood species), including two exotic and two European differentiated by density varied from 385 $kg·m^{-3}$ up to 847 $kg·m^{-3}$ were subjected to tests, namely: alder (*Alnus glutinosa* Gaertn.), oak (*Quercus robur* L.), jatoba (*Hymenaea courbaril* L.) and obeche (*Triplochiton scleroxylon* K. Schum.). Each group of material was subjected to strength tests according to the following standards: PN-D-04100 (1977), PN-D-04101 (1977), PN-D-04102 (1979), PN-D-04103 (1977), PN-D-04123 (1975) and PN-D-04227 (1977). Basic physical-mechanical properties of wood are showed in Tab. 1.

Tab. 1: Physical and mechanical properties of analyzed materials.

Species	**Scientific name**	**W (%)**	**ρ_w ($kg·m^{-3}$)**	**R_{gw} (MPa)**	**E_g (102 MPa)**	**R_{cl} (MPa)**	**E_{cl} (MPa)**
Alder	*Alnus glutinosa* Gaerta.	5.9	538	113.7	89.5	65.2	50.4
Obeche	*Triplochiton scleroxylon* K.Schum.	6.1	385	63	53.4	37.9	32.9
Jatoba	*Hymenaea courbaril* L.	9.2	847	154.1	143.3	102.4	67.2
Oak	*Quercus robur* L.	7.5	737	139.1	112.1	78.4	58.1

Note: W- irrelative moisture content of wood; ρ_w- density; R_{gw}- strength during bending; E_g- modulus of elasticity during bending; R_{cl}- strength during compression along the grains; E_{cl}- modulus of elasticity during compression along the grains.

Preliminary researches were conducted in the Faculty of Wood Technology in Warsaw, Poland. Drilling tests were performed on a computer numerical control (CNC) working centre Busellato Jet 130 (SCM Group, Rimini, Italy). There were prepared twelve work samples (three work samples made of each group of material). Fifteen holes in each work sample were drilled with a 10 mm diameter polycrystalline diamond drill bit. The rotational spindle speed was set to 6000 RPM and the feed speed at 0.6 m·min^{-1}, 1.2 m·min^{-1} and 1.8 m·min^{-1}. These values coincided with parameters held by the producer of the tool (Fig. 1). The range of parameters was a little wider than shown in the diagram to obtain full characterization of the analyzed material. The torque and the axial force were measured with Kistler transducers (Kistler 9345A, Kistler 5073A; Kistler GmbH, Winterhur, Switzerland) and were recorded with a National Instrument Data Acquisition System (NI PCI 6034E, LabVIEW, version 7, Austin, TX, USA). Details of the measurement chain are shown in Fig. 2. The dimensions of workpieces were the following: 135 × 35 × 25 mm.



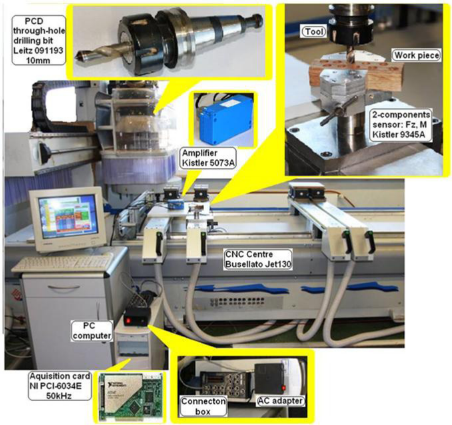


Fig. 1: Cutting parameters recommended by Leitz.

Fig. 2: View of CNC drilling testing bench.

Additional tests by Stone Assistance

Four samples obtained from the same four groups of material described earlier were prepared according to demands of measurement stand in Belgium and sent to Stone Assistance of University of Mons where two different methods to obtain machinability indicators were applied; a scratching test and the micro-drilling test, which are both characterized below.

The scratching test

The principle of the scratching test consists in removing the tested material by the cutting action of a tool or cutter, at a constant depth of cut (d), and moving at a fixed velocity (v). The testing procedure consisted of performing cutting tests, with a 10 mm-wide rectangular sharp cutter that deepened a groove at depths of cut varying from 0.05 mm to 0.50 mm by increments of 0.05 mm (Fig. 3). This procedure was repeated four times as it was shown in fig.7. Tests were performed with a back rake angle θ of 15°. The procedure assumed that the cutter was nominally sharp, and the depth of the cut was small enough to neglect the side effect according to Dagrain et al. (2004).

The tangential (F_t) and normal forces (F_n) on the cutter, were measured continuously while testing at a sampling frequency that can be set within 1 Hz and 600 Hz, typically 200 Hz. Testing velocity v was set at 10 $\mathrm{mm \cdot s^{-1}}$.

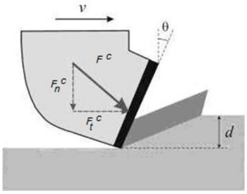


Fig. 3: Definition of the different parameters considered in material cutting (Dagrain et al. 2004).

The scratching tests were performed on an instrumented shaper, which allows for easy clamping of the samples. The results were analyzed in a diagram presenting the averaged forces (F_t and F_n) versus the cross-sectional area of the cut A_c (Fig. 4). Equations below describes the method used for the calculation of area of cross section A_c (1), tangential force F_t (2) , and normal force F_n (3):

$$A_c = wd \tag{1}$$
$$F_t = \varepsilon A_c \tag{2}$$
$$F_n = \zeta \varepsilon A_c \tag{3}$$

where: w - is the cutter width (mm),
d - the depth of the cut (mm),
ε - is the intrinsic specific energy,
ζ - the friction on the cutting face.

The intrinsic specific energy (ε), is given by the slope of the linear regression on the tangential forces. It has been found in geomaterial characterization that the intrinsic specific energy is well correlated to the uniaxial compressive strength.

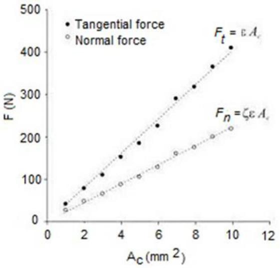


Fig. 4: Forces versus cross-sectional area of the cut (Dagrain et al. 2004).

The micro-drilling test

The concepts of the micro-drilling test were similar to the ones of the scratching test. The main difference was that in micro-drilling the blades were rotating instead of translating like in the scratching test.

The micro-drilling test consisted of drilling holes into the material to characterize, by use of a drill bit, the known radius (r = 5 mm), at imposed rotational speed (RPM = 250 $\mathrm{rev \cdot min^{-1}}$), and imposed rates of penetration (*ROP* = 0.050 ÷ 0.300 mm·rev^{-1} by step of 0.050 mm·rev^{-1}). All parameters were set before testing and remained constant while testing.

The weight on bit *W* (thrust force), the torque on bit T, the rotational speed *RPM*, and the rate of penetration *ROP* were measured and recorded continuously while testing. The micro-drilling tests were performed on a conventional drilling fully instrumented and automated.

The theoretical approach of the micro-drilling test may be derived from the equations of linear cutting. It can be demonstrated from rock cutting equations that the weight on bit *W* (thrust force) and the torque on bit *T* are related to the rate of penetration (*ROP*), the rotational speed (*RPM*), the geometrical properties of the bit (bit radius r, number of blades n, and state of wear λ), the material properties (intrinsic specific energy ε), and to the friction law on the cutting face (ζ factor), and on the wear flat (contact stress σ and friction coefficient μ) by the below relations.

The analysis of the testing results was performed according to the equations based on and torque on bit *T* and the weight on bit *W* (thrust force) versus *ROP/RPM* ratio (Figs. 5, 6).

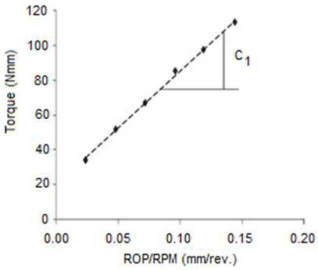


Fig. 5: Graphical interpretation of C1 indicator.

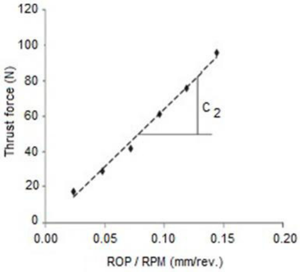


Fig. 6: Graphical interpretation of C2 indicator.

Eqs. 4 and 5 used for the calculation of the weight of bit W (thrust force) and the torque (T) are presented below:

$$W = r\frac{ROP}{RPM}\zeta\varepsilon + n\sigma r\lambda \tag{4}$$

$$T = \frac{r^2}{2}\frac{ROP}{RPM}\varepsilon + n\frac{r^2}{2}\mu\sigma\lambda \tag{5}$$

The analysis of the data consisted in measuring the slope of the best linear trend fitting the data (C1 in the T vs. ROP/RPM diagram and C_2 in the *W* vs. *ROP/RPM* diagram). The intrinsic specific energy ε in micro-drilling is given by Eq. 6:

$$\varepsilon = \frac{2C_1}{r^2} \tag{6}$$

The ζ factor is given by Eq. 7:

$$\zeta = \frac{r}{2}\frac{C_2}{C_1} \tag{7}$$

Note that the comparison of the intrinsic specific energy ε and ζ factors must be done carefully. Scratching and micro-drilling tests are performed with tools that do not present the same geometrical properties. The micro-drilling bits are very thin in comparison to the cutters used in scratching, and are working at a lower depth of cut. It is normal to measure intrinsic specific energy that presents a different order of magnitude in micro-drilling. This has been discussed in literature and is explained by a scale factor and a tridimensional effect. The ζ factor is related to the rake angle of the cutting face and to the flow of particles on the surface. Both tests are not performed with the same rake angle, and it is, therefore, normal to measure different ζ factors.

The tests performed on building materials (stones, mortars, bricks, etc.) have shown a strong correlation between the intrinsic specific energy in scratching and the C1 parameter obtained in micro-drilling.

Testing procedures

Dimensions of the samples amounted 300 × 120 × 25 mm and were fitted to the technical requirements of measurements on piezoelectric platform. First, the samples (one made of each group) were processed using multiple scratching with varying heights of the cutting layer as shown in Fig. 7. Then, on the bottom of preliminarily made groves, through holes were made by a conventional drilling machine. The scheme of machining is shown in Fig. 7. In each work sample, 4 passages on given depth with knife with rectangular shape and 24 through holes (12 on each side of work sample) were made. The parameters of the machining process (depth of each pass etc.) concerning as well scratching test as micro drilling tests where discussed earlier where principles of indicators assessment were showed.

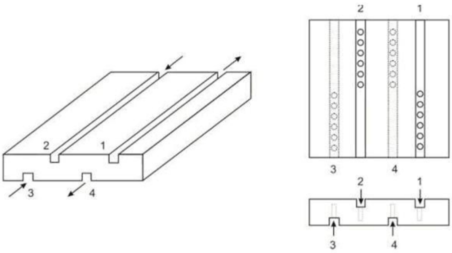


Fig. 7: Schematic of scratching and drilling.

Oak was used as a reference material, with which the average value of thrust force and torque, values of C1, C2, specific cutting resistance during scratching ε, thrust coefficient during scratching ζ, specific cutting resistance during drilling ε, and friction coefficient during drilling ζ were compared.

According to above statements relative indicators of machinability were calculated with the following equations (Eqs. 8-15):

$$MI_{T\text{-drilling1}} = (M_{oak} / M_i) \tag{8}$$

$$MI_{F\text{-drilling1}} = (F_{oak} / W_i) \tag{9}$$

$$MI_{\varepsilon\ scratching} = (\varepsilon\ \text{scratching}_{\ oak} / \varepsilon\ \text{scratching}_{\ i}) \tag{10}$$

$$MI\zeta\ \text{scratching} = (\zeta\ \text{scratching}_{\ oak} / \zeta\ \text{scratching}_{\ i}) \tag{11}$$

$$MI_{C1} = (C1_{oak} / C1_i) \tag{12}$$

$$MI_{C2} = (C2_{oak} / C2_i) \tag{13}$$

$$MI\varepsilon\ \text{drilling} = (\varepsilon\ \text{drilling}_{\ oak} / \varepsilon\ \text{drilling}_{\ i}) \tag{14}$$

$$MI\zeta\ \text{drilling} = (\zeta\ \text{drilling}_{\ oak} / \zeta\ \text{drilling}_{\ i}) \tag{15}$$

where, M_i, F_i, ε scratching $_i$, ζ scratching $_i$, $C1_i$, $C2_i$, ε drilling $_i$, and ζ drilling $_i$ were related to i-th wood species.

The above relative machinability indicators were used in the assessment of WPC machinability by Wilkowski et al. (2013a) during drilling. Usefulness of relative indicators of machinability was confirmed by Głobocki et al. (2009). This methodology allowed a much easier comparison between extremely different materials. The wide applications of oak wood are the reason that this wood species was assumed in this work as a reference material. The obtained data were correlated to the mechanical properties of the material.

RESULTS

The obtained data were processed so that determination coefficients R^2 between relative machinability indicators that were received during drilling on the CNC machine Busellato Jet 130 (MI_T , MI_F) and relative indicators derived from the conventional drilling machine and the scratching measurement received at Stone Assistance. Moreover correlations between all mentioned above relative machinability indicators and physical and mechanical properties of analyzed wood species were taken into account. The results are summarized in Tab. 2.

Tab. 2: Summary of R^2 value for all relative machinability indicators and physical and mechanical properties of analyzed wood species.

	MI_T	MI_F	$MI_{\varepsilon\ scratching}$	$MI_{\zeta\ scratching}$	MI_{C1}	MI_{C2}	$MI_{\varepsilon\ drilling}$	$MI_{\zeta\ drilling}$	ρ_w	R_{gw}	E_g	R_{cl}	E_{cl}
MI_T	1.00												
MI_F	**0.96**	1.00											
$MI_{\varepsilon\ scratching}$	0.85	**0.94**	1.00										
$MI_{\zeta\ scratching}$	0.77	0.78	0.88	1.00									
MI_{C1}	0.39	0.59	0.73	0.47	1.00								
MI_{C2}	0.87	**0.97**	**0.98**	0.79	0.74	1,00							
$MI_{\varepsilon\ drilling}$	0.39	0.59	0 .72	0.47	**1.00**	0.74	1.00						
$MI_{\zeta\ drilling}$	**0.97**	**0.96**	**0.92**	0.89	0.46	**0.91**	0.46	1.00					
ρ_w	**0.97**	**1.00**	**0.94**	0.80	0.56	**0.97**	0.56	**0.97**	1.00				
R_{gw}	**0.96**	**0.98**	0.85	0.66	0.50	**0.92**	0.49	**0.91**	**0.97**	1.00			
E_g	**0.93**	**0.98**	0.87	0.64	0.57	**0.94**	0.57	0.89	**0.97**	**0.99**	1.00		
R_{cl}	0.83	0.72	0.49	0.36	0.15	0.58	0.14	0.69	0.73	0.84	0.79	1.00	
E_{cl}	**0.99**	**0.92**	0.78	0.71	0.31	0.81	0.31	**0.94**	**0.93**	**0.95**	0.90	0.88	1.00

It was assumed that when value of determination coefficient R^2 exceeded a level 0.9, this relationship can be perceived as strong. Therefore, the summarized results, shown above, proved the strong relationships between indicators assessed on the CNC machine (MI_T, MI_F) and indicator based on friction coefficient during drilling on the conventional drilling machine ($MI_{\zeta\ drilling}$) or indicator MI_{C2}. It follows from the fact that R^2 exceeded level 0.9.

Especially the value of R^2 between thrust force and indicator MI_{C2} ($R^2 = 0.97$) as well as indicator $MI_{\zeta\ drilling}$ ($R^2 = 0.96$) achieved a very high level. In terms of torque, the level of correlations related to $MI_{\zeta\ drilling}$ ($R^2 = 0.97$) was also very high. Although, in case of indicator MI_{C2} , R^2 for was different and was slightly lower ($R^2 = 0.87$).

Similarly, it is worth to point out relationships between indicator based on specific cutting resistance ($MI_{\varepsilon\ scratching}$) obtained with scratching test with an elementary cutter and torque or thrust force with values R^2 amounted 0.85 and 0.94, respectively.

Worse results were proved for correlations between indicators obtained with usage of the CNC machine, and indicator MI $_{\zeta\ \mathrm{scratching}}$. Determination coefficient R^2 for, MI_T, and MI_F amounted to 0.77 and 0.78, respectively. Whereas, between the values of MI_T, MI_F (CNC machine), and indicator MI_{C1} were not estimated so satisfactory results.

DISCUSSION

As was mentioned earlier, relationships between relative machinability indicators and relative values of mechanical and physical properties of analyzed wood species were calculated too. From Tab. 2 it was shown that the strongest correlations were noticed for wood density ρ_w that has crucial influence for material hardness. This conclusion is in coincidence with previous work of Wilkowski et al. (2011). In this researches addition of lignin binder in wood-fiber material increased hardness of outer surface in Brinnell scale, respectively: 137.43 $N \cdot mm^{-2}$ for standard panel and 249.12 $N \cdot mm^{-2}$ for modified panel. In result, all machinability indicators, namely: cutting power, cutting coefficient referred to torque and cutting coefficient referred to thrust force noticed statistically important changes.

These statements refer to another works too. Podziewski et al. (2018) proved that machinability indicator CFPI (cutting force problem indicator) in drilling that encompassed in this work as well thrust force as torque shows similar performance. It means that correlation coefficient R^2 between CFPI and density and hardness achieved more than 0.9 at $p<0.005$. It was strongly evident during separate analysis of fibreboard and veneer panels. Equally important correlations were not observed in case of particleboard (barely: $R^2<0.3$ and $p>0.5$). But, this may have been done due to relatively low diversity regards to density and hardness.

As far as it concerns only one kind of wood-based material (MDF) according to Lin et al. (2006), the difference between two kinds of panels with density 740 $kg \cdot m^{-3}$ and 1000 $kg \cdot m^{-3}$ exceeded about 30% depend on cutting direction. Very clearly this phenomenon was observed in case of sawing. Researches concerning machinability indicator for variety of standard wood-based materials carried out by Wilkowski et al. (2013a, 2013b) revealed strong correlations between cutting resistance and density of material. Relative machining indicator (MDF board assumed as reference) varied in range of 18-100%. The lowest (poor machinability) were noticed for compressed plywood and the highest for porous fiber board (excellent machinability).

Moreover, Wieloch et al. (1999) proved evident influence of material density on proper cutting work too. In general, because of the strong influence of density on material performance subjected to loading it can be assumed that other mechanical properties will be correlated with density. For instance the modulus of elasticity during bending Eg or bending strength Rgw proved to be strong relationships with relative machinability indicators. The R^2 regards to relationships between modulus of elasticity during bending and some of the machinability indicators exceeded the value 0.9. The MI_T belongs to the indicators that, in the most reliable way, reflected physical and mechanical properties of wood such as density ρ_w (R^2 = 0.97) and modulus of elasticity during compression E_{cl} (R^2 = 0.99). Similar results were obtained for relationships between MI_F and density (R^2 = 1) or modulus of elasticity during compression E_{cl} (R^2 = 0.92). Slightly weaker, although very high values related to the above mentioned physical and mechanical properties were noticed in the case of MI $_{\zeta\ \mathrm{drilling}}$, where R^2 for ρ_w and E_{cl} were amounted 0.97 and 0.94, respectively. The value of R^2 for correlations between MI_{C2} and density ρ_w also achieved a very high level (R^2 = 0.97). However, this machinability indicator was slightly worse regards to modulus of elasticity Ecl (R^2 = 0.81).

Non-satisfactory correlations were proven for relationships between mechanical properties of wood and indicator MI_{C1} or $MI_{\varepsilon\ drilling}$. According to tab. 2, the value of R^2 for relationships between these two machinability indicators and physical and mechanical properties of wood vary in range 0.15 – 0.57.

Results showed that the comparison of the reliability of the materials' machinability depended on many factors. One of these factors was the kind of machining. The most appropriate criterion, which should be assumed to verify their effectiveness, is their correlations with the mechanical properties of wood. The range of the results was very wide. First results should be confirmed by doing more tests on other species to get more precise correlations between the different parameters.

Undoubtedly, the most reliable assessment of material properties ensured machinability indicators based on the measurement of thrust force and torque. Among others, machinability indicators were useful in enhancing high levels of correlations between mechanical properties of wood and indicators MI_{C2} and $MI_{\zeta\ drilling}$.

However, results obtained by using the measurement of the scratching stand turned out worse. The source of this situation could be too little data in this work. Additionally, there were some problems with the geometry of the cutter holder. This should be improved by modifying the actual testing parameters. However, it does not mean that this method is fully not applicable. The tool geometry in this study was not fully fitted to this kind of material. Therefore, further experiments with the usage of an elementary cutter as a machinability assessment method should be continued.

Even, if the first results obtained on those pieces of wood were very promising, there still need to be some improvements made. First of all, the negative rake angle used traditionally for the scratching tests in rocks and other building materials is not well adapted, and it should be changed into a positive. This would help the cutting to be eliminated while testing. A negative rake angle in wood tends to create the phenomena of balling, which generates an increase of forces.

CONCLUSIONS

According to obtained results the following conclusions can be formulated:

1. The strongest relationships between machinability indicators obtained directly from the platform installed on the CNC machine were noticed for dependence between MI_F and $MI_{\varepsilon\ scratching}$ (R^2 = 0.94) or MI_{C2} (R^2 = 0.97).
2. High values of R^2 were proven to be between $MI_{\zeta\ drilling}$ and MI_F (R^2 = 0.96) as well as MI_T (R^2 = 0.97).
3. As it concerns physical and mechanical properties of wood, material density (ρ_w) is correlated the most with machinability indicators MI_F and MI_T.
4. All of the analyzed physical and mechanical properties (except strength during compression along the grains R_{cl}) were strongly correlated with MI_F and MI_T.
5. Among machinability indicators proposed by Stone Assistance, the most promising machinability indicator that turned out to be best correlated with physical and mechanical properties was MI_{C2} and $MI_{\zeta\ drilling}$.

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