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ORIGINAL ARTICLE

The influence of technical characteristics of wood milling tools on its wear performance

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Abstract Influence of technical and chemical characteristics of industrial wood milling tools on its wear was analysed. Four tools of different manufacturers were subjected to the research. Lithuanian oak wood was chosen for the research as a reference material. Behaviour of cutting tools was assessed on the adopted industrial thickness planer SR3-6 with cutting speed of 31 m/s. Wear performance was evaluated on milling the specimens until 3200 m of true cutting length. Summarising achieved results, the following can be stated: chemical composition of tool and heat treatment schedule has great impact on the tool edge wear. The highest wear resistance was reached on testing tools made of CT01M-LA2; tools made of high-alloyed tool steel 8X6HΦT have presented the highest cutting edge radius and edge recession in each type of test as compared with tools made of high-speed tool steels Z80WCV18-04-01/18-0-1 and HS18-0-1, respectively. All these tools are suitable for oak wood processing. The high-alloyed tool steel shows similar wear performance as high-speed tool steels.

Keywords Wood milling · Oak wood · Wear of tool · Wear resistance

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Introduction

Milling process is one of the most widely used processes in wood and wood-based materials processing. Strehler et al. [1] and Hernádez-Castaneda et al. [2] show that alongside the quality of machined wood surface, the tool lifetime is an essential question in the industrial complex wood treatment process. Wood is readily available heterogeneous material with plenty of varieties, which is used in the furniture, packing, building constructions, beam flashings, flooring and panelling, window frames. The majority of wood processing companies specialise in the manufacture of planed-milled products. According to Horman et al. [3] and Vobrouček [4] during processing of wood by planning milling, the key point is to ensure high-quality machined surface with low processing costs; however, it is impossible to attain without analysis of various properties and technological parameters: wood moisture, thermal effects, cutting and feed speed, proper tool selection, toll geometrical parameters, toll material, etc. Another very important point in wood processing is to know which material would be machined: different process conditions are necessary for each species of wood to reach optimal results, wherefore it is not possible to explore just one type of cutting tool to achieve the best efficiency of process and high quality of products. A good thermal conductivity of the tools is essential in wood processing, because no cooling can be used in this process; it was analysed by Strehler et al. [5] and Costes et al. [6]. Temperature of the cutting tool affects the tool cutting edge blunting and wear, because the primary properties of tool material such as hardness, fracture toughness and chemical stability degrade on rising tool's temperature [7]. The heat generated during cutting process negatively affects the quality and accuracy of the product, herewith the life time of tool.

Great demand of today's wood industry has resulted in intense development of the cutting tools, which unfortunately do not always have characteristics allowing a complete exploitation of the machinery. It is evident that the main problems in wood industry arise from differences in physical and chemical properties between wood and metal [8, 9]. Good machinability of wood allows high cutting and feed speed, herewith natural wood contains some water, which makes tooling very corrosive. Natural defects of wood cause blunting of tool edges, so extremely hard brittle materials are not suitable in this case. Hardened steels, high-speed tool steels, stellites, tungsten carbide and polycrystalline diamond tools have been used recently in wood transformation. The most common of them are alloyed tool steels and high-speed tool steels, because of their sufficient wear performance and relatively low cost, herewith sintered carbides, polycrystalline diamond tools, different anti-wear multilayer coatings have been used recently [10]. The dominant wear of wood cutting tool is abrasion; however, erosion of tool material and blunting of its edges, which limits possibilities of tool application, can be observed. It was stated in the majority of works that final quality of wood products depends on correct choice of cutting tool type, cutting conditions and tool performance; selection of appropriate tool material for a certain application is directly influenced by the characteristics of material to be machined [11, 12]. As one of the major properties of final wood products, surface roughness greatly depends on the anatomic characteristics of wood, direction of wood grain and cutting tool characteristics [13, 14].

Different types of wood milling tools are used in industry: solid tools [made of alloy tool steel (SP), high-alloyed tool steel (HL) or high-speed tool steel (HS)] and built-on hard alloy blades or different high wear resistance coatings. Shank of built-on tool is made of high carbon or alloy tool steel, while cutting edge is produced of stellites (ST) or plates of tungsten carbide (HW). The cutting edge of more advanced tools is made of polycrystalline (PKD) or monocrystalline (MKD) diamonds. Solid cutting tools are generally used for natural wood milling, planning and profiling contain chromium (Cr) as the main alloying element. Chemical composition of tool steel plays an essential role in both tool performance and final quality of wood product.

Batch of HS tool steels is designed to be used particularly for making of cutting tools. In the wood cutting industry, the milling speed is very high and no cooling can be applied, so the ability to maintain the hardness and wear resistance at elevated temperatures (the property known as red hardness) is the main reason why those tools are widely used. Basic alloying elements ensure above-mentioned properties of tool. Tungsten (W) has an ability to form hard abrasion-resistant particles; it induces red hardness and improves hardenability. Cr easily combines with carbon (C) creating hard and high wear resistance chromium carbides, at the same time giving to the substance heat resistivity. Cr and nickel (Ni) content in the solid tool guarantees high enough corrosion resistance which is necessary for such a type of tooling. Vanadium (V) reduces the sensibility of steel to overheating, increases heat conductivity, and stimulates homogeneous distribution of carbide phase which can cause crumbling of cutting edges. Molybdenum (Mo), in the same way as Cr, creates carbides very easily; the presence of this element in the steel composition helps to create fine-grained structure and increase hardenability; therefore, this chemical element presents in almost all HS steels, and it also increases the tensile strength at elevated temperatures.

SP and HS steels are used to produce wood milling tools, sawmills and other tools for wood processing machines. Tools made of SP steels are suitable for processing of both wet and dry timber, while high HS steels are used exclusively for dry woods [15]. Almost all SP and HL are rich in Cr, which increases hardenability of steel, initiates formation of special carbides on hardening, either increases secondary hardness and heat resistance of steel; chromium carbides formed during treatment reduce wear of tool.

HS steels are used for manufacturing of wood cutting tools which heat up during process; wear resistance of this kind of steel is very high. High heat resistance is ensured by content of W, Mo, V and cobalt (Co) in the steel composition; using this type of tools operation cutting speed is much higher than using SP steels [16].

The objective of this study is to test and compare wear behaviour of four wood millings tools from different suppliers, to analyse influence of its chemical composition and distribution of carbide phase in the microstructure on the tool edge recession and wear performance, while milling comparatively hard oak wood specimens on an industrial thickness planer with constant cutting speed and different feed rates.

Materials and methods

For the experimental analysis, four standard wood cutting tools from different suppliers made of SP steel and HS steels were chosen. Standard grades and chemical composition presented by suppliers are indicated in Table 1.

All cutting tools under the experiment were strait sharpened; its edges convergence was achieved by grinding procedures of wood cutting tool done by suppliers.

Table 1 Chemical composition of standard wood cutting tools

Chemical composition (wt%)	Wood milling tools			
	No. 1 8X6HΦT OTЌ-14	No. 2 ESS-HSS18	No. 3 HS 18 Y 28	No. 4 CT01M-LA2
C	0.80–0.90	0.75–0.83	0.70–0.78	0.73–0.83
Si	0.15–0.35	≤0.50	≤0.45	≤0.50
Mn	0.15–0.40	≤0.40	≤0.40	≤0.40
Ni	0.90–1.30	–	–	–
S	≤0.03	≤0.03	≤0.03	–
P	≤0.03	≤0.03	≤0.03	–
V	0.30–0.50	1.00–1.30	1.00–1.20	0.90–1.20
Ti	0.05–0.15	–	–	–
Cr	5.00–6.00	3.50–4.50	3.80–4.50	3.50–4.50
Mo	≤0.20	≤1.00	–	≤1.00
W	≤0.20	17.2–18.7	17.5–18.5	17.2–18.7
Co	–	–	–	≤1.00

Accurate dimensions of tools: length L, width B and thickness S were measured using electronic calliper with the accuracy of ±0.001 mm. Accuracy of sharpness angle β was ensured by using universal protractor Vogel No. 4443 with 5′ accuracy. Tools were weighted on electronic scales with an accuracy ±0.01 g for determination of density. Hardness measurements were accomplished on the tools surface along the tool edge using Rockwell tester TK—2 with diamond indenter. The stylus tip surface roughness tester, profilometer Mahr MarSurf PS1 (the radius of its diamond tip was 2 μm, measurement angle 90°, and scanning length was 5.6 mm, cutoff filter 0.8 mm), was used for measurement of average roughness R_a, mean peak-to valley height R_z, and maximum roughness R_{max}; 5 values of roughness were taken and average presented. The surface roughness was measured in the longitudinal direction at the interval of 10 mm, so 5 measurement positions in total were defined for each cutting tool on the rake and clearance face. The surface evaluation was performed starting from cutting side. Parameters of cutting tools and cutting tool geometry and location of measurements are presented, respectively, in Table 2 and Fig. 1.

Cutting tools microstructure and its morphology were determined using optical microscope Carl Zeiss LM 10. Specimens for the analysis of microstructure were made from each of wood cutting tools, then side surfaces were grinded, and examined. The scheme of specimens cutting position is presented in Fig. 1a.

Oak wood (*Quercus robur*) grown in Lithuania was chosen for the testing of cutting tool performance; specimens with dimensions of 100 mm × 45 mm × 1000 mm (R × T × L) were prepared avoiding all the defects of natural wood. The number of annual rings per 1 cm was counted up on the end section of specimens. Moisture tester Gann Hydrometter Compact A was used for the estimation of average moisture content (accuracy ±1%). Finally, for the determination of wood density samples with dimensions 20 mm × 20 mm × 30 mm (R × T × L) were produced, and were scaled on electronic balance (AND HF-12006 GF; accuracy ±0.01 g). Testing conditions were the same for all specimens: ambient temperature 18 ± 2 °C, relative air humidity—60 ± 5%, when physical characteristics of oak wood samples were as follows: moisture content—9.50 to 10.4%, number of annual rings per 1 cm—5.07 to 5.25, and density—518 to 570 kg/m^3.

The behaviour of standard wood milling tools was assessed on the adopted for the particular experiments industrial thickness planer SR3-6 according to the scheme of longitudinal milling (Fig. 2). Longitudinal milling is the most frequently used method to obtain flat surfaces in wood processing industry [17–19]. This type of operation ensures high surface quality. Wood specimens were processed by cutting speed (v_c) 31 m/s with four different feed speeds (v_f): 3.00, 6.00, 9.00 and 12.0 m/min. Average chip thickness was alternated changing feed per one insert (f_z): 0.50, 1.00, 1.50, 2.00 mm. Wear performance was evaluated on milling the specimens until 3200 m of cutting length.

Tool geometry was analysed by alternations of cutting edge radius ρ (μm), and edge recession A_μ, (μm) of tools [20–23].

Values of cutting edge radius were determined applying lead impression method using optical tool measurement microscope of 2nd accuracy class (GOST 9038-80) and digital camera with resolution 640 × 480. Edge radius values were registered at the intervals of true cutting length L which is the cutting way of tool in the wood: 0, 50, 100, 150, 200, 400, 800, 1200, 1600, 2400, and 3200 m in five places and average values were analysed; error of

Table 2 Parameters of wood cutting tools

Parameters	Wood milling tools			
	No. 1	No. 2	No. 3	No. 4
Designation by supplier	8X6HΦT OTK̆-14	ESS-HSS18	HS 18 Y 28	CT01M-LA2
Standard designation	8X6HΦT	Z80WCV 18-04-01/18-0-1	HS 18-0-1	HS 18-0-1 (B18)
Standard	GOST 5950-73/ DIN-EN 847-1	NF A 35-590(92) ISO 4957	DIN 1.3355/ ISO 4957	UNI 2955-82 ISO 4957
Dimensions (mm) L/B/S (Fig. 1)	60/40/3	60/35/3	60/35/3	60/30/3
Tool geometry	Clearance angle α 20 ± 5′, sharpness angle β 40 ± 5′, rake angle γ 30 ± 5′, cutting angle δ 60 ± 5			
Mass (g)	54.2	51.7	40.8	41.8
Density (kg/m^3)	7360	8119	8092	8144
Hardness (HRC)	57	61	61	61
Surface roughness (μm) (Fig. 1)				
Rake face $R_a/R_z/R_{max}$	0.518/3.35/5.18	0.281/1.79/2.92	0.251/2.11/2.98	0.168/1.28/2.24
Clearance face $R_a/R_z/R_{max}$	0.600/4.11/4.90	0.272/2.30/2.72	0.285/3.39/4.23	0.430/3.68/3.95

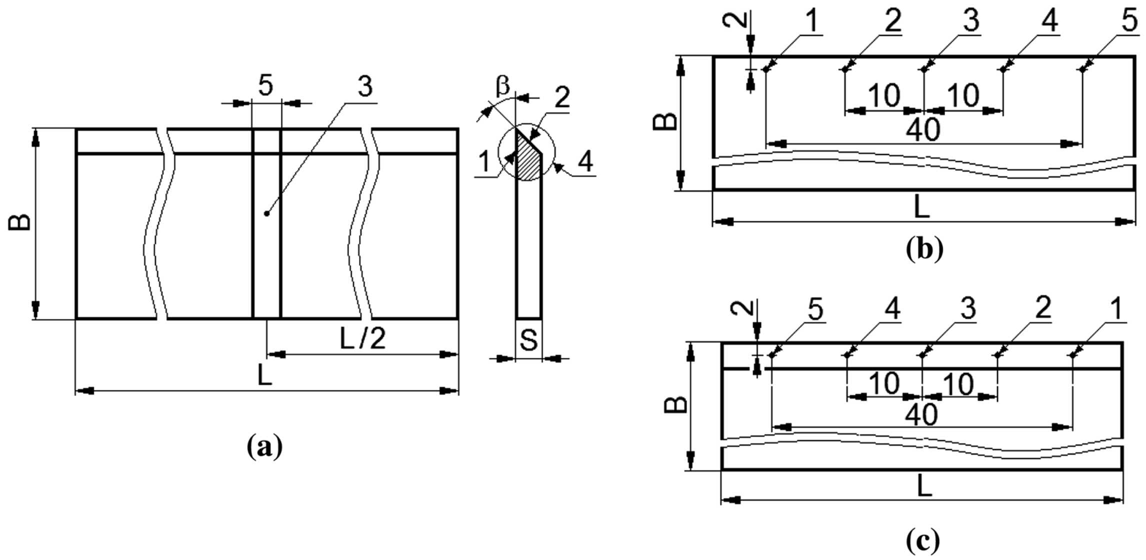


Fig. 1 Wood milling tool: **a** dimensions, *1* rake face, *2* clearance face, *3* specimen, *4* area examined using microscope; **b** rake face, **c** clearance face; *1–5* location of hardness and roughness measurements

measurements accuracy ±2 μm. Reference surface was used for the optical visual observation of edge recession using microscope, and values were registered in the same intervals of cutting length.

Cutting power P was figured out measuring available power and taking out an idle motion power. Available and idle motion power was measured using device K506 (GOST 8476-78, accuracy class 0.5) with the accuracy of 5 W. The device was attached to the stand milling mechanism of electrical motor in parallel mode; an idle motion power was gauged before milling operation, while operating active power measured during whole process of milling.

Results and discussion

Four standard industrial tools from different suppliers were subjected to oak wood milling process. Analysing results of cutting edge radius, it can be stated that trend of wear mechanism of all milling tools is conventional; four main stages of wear are observed: first until 400 m, second—from 400 to 800 m, third—from 800 to 1600 m, and the last—from 1600 to 3200 m of cutting length. The first stage gave the most intensive wear at all feeds per insert. In the next stage of process wear slowed down, and the growth of cutting edge radius decreased. Crumbling of edges was replaced by continuous and stable tribological

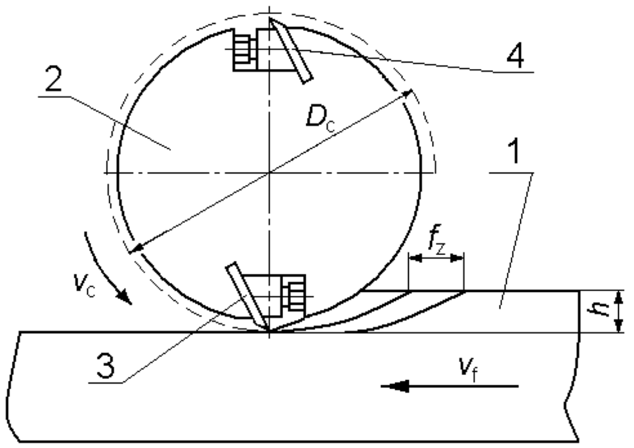


Fig. 2 Scheme of longitudinal milling: *1* specimen, *2* cutterhead, *3* examined cutting tool, *4* balance tool, D_c cutting diameter (103 mm), v_c direction of cutting speed, v_f direction of feed rate, f_z feed per insert, *h* cutting depth (2 mm)

wear, which was common for all tools. This stage revealed differences between wear of milling tools (Figs. 3, 4). Wear intensity slowed down in the third section of cutting length. Linear dependence of cutting edge radius on cutting length was observed in the last stage of experiment. Wear results in Fig. 3 show that cutting edge radius of cutting tool no. 1 made of high-alloyed tool steel 8X6HФT increased the most. Wear performance of milling tool no. 4 made of high-speed tool steel HS 18-0-1 showed the best results at each feed per insert. Definitely it depends on chemical composition of tool: with very similar carbon content (~0.8%), material of tool no. 4 (Table 1) is richer in tungsten, which forms hard particles; hardness of these tools differs in few Rockwell hardness points (HRC).

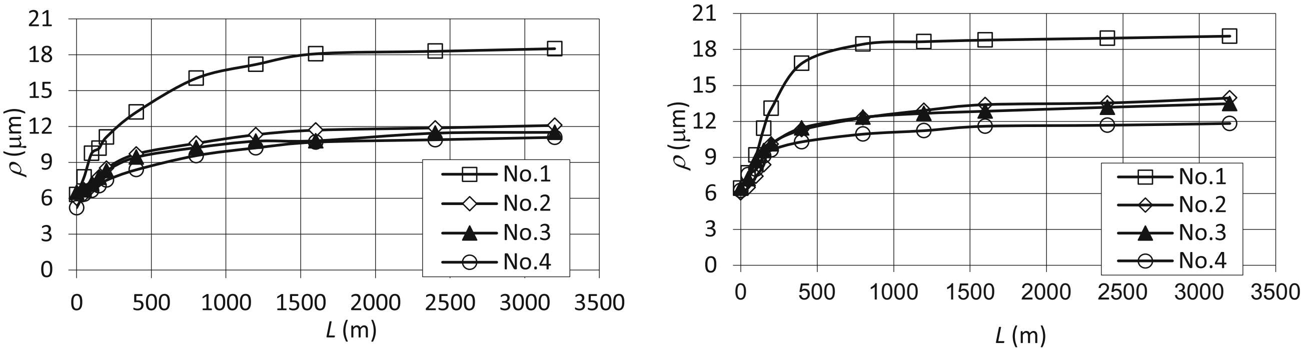
More detail estimation of first stage of milling till the 100 m of cutting length points out the almost equal increment of edge radius for all milling tools; passing the limit of 100 m cutting tool no. 1 starts fray more intensively as compared with tools nos. 2, 3 and 4. On reaching 200 m of cutting path, difference in increment of cutting edge radius exceeds 25.7% (nos. 1 and 4). This difference increases in all further stages of process and makes up 32.1% reaching 400 m, 36%—800 m of cutting length. Segment of cutting path from 1600 to 3200 m properly shows stable wear process where the values of edge radius are just slightly increased.

Tool no. 1 made of high-alloyed steel reaches hardness of 57 HRC after hardening and low temperature (250 °C) tempering. Microstructure consists of tempered martensite and carbides inclusions, which are uniformly distributed, just in some areas of tool coarse primary carbides and negligible linear distribution of carbides are observed (Fig. 5a).

Hardness of rich in tungsten high-speed tool no. 2 (61 HRC) is reached after hardening and tempering at 320 °C. Microstructure of tool consists of grains of austenite and martensite; the average size of grain is no. 11. Low tempering temperature for this type of steel does not allow to reach secondary hardness, wherefore steel does not possess high temperature resistance. Carbide phase is distributed uniformly; few coarse carbides can be seen (Fig. 5b).

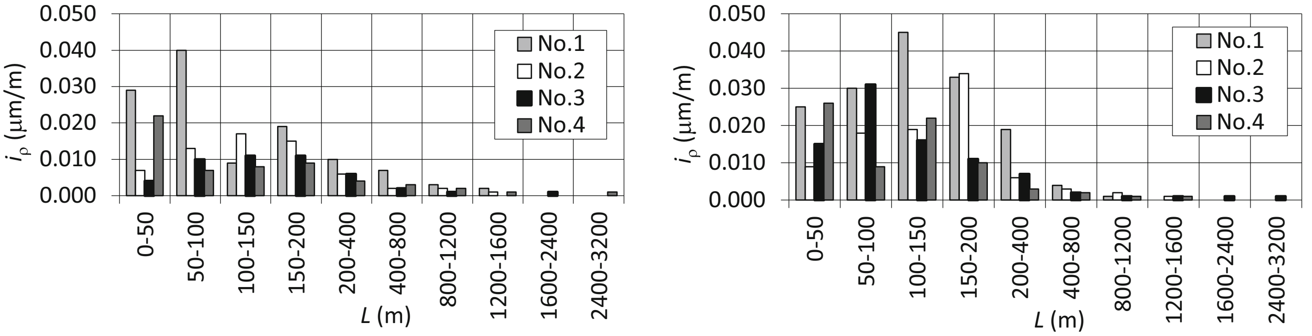
Almost analogous structure of tool no. 3 (61 HRC) assures that these tools were subjected to the very similar schedule of heat treatment (Fig. 5c).

Wear test results of tools made of high-speed tool steel (nos. 2, 3, 4) are very similar; even hardness of these tools is the same—61 HRC, but the best wear performance was reached testing tool no. 4. Microstructural analysis revealed other important issue: tools nos. 2 and 3 were heat treated according to similar schedule; size of austenite grain in both is no. 11 (fine) according to the standard scale. Microstructure of tool no. 4 (Fig. 5d) differs: tool was tempered at higher temperature or required hardening temperature was not reached, because microstructure consists of tempered martensite and fine uniformly distributed disperse carbides. Course enough primary carbides and light high alloyed trails are observed in the structure that shows segregation of alloying elements in the tool blank.



(a) **(b)**

Fig. 3 Variation of cutting edge radius ρ (µm) at different values of feed per insert f_z: **a** $f_z = 0.50$ mm, **b** $f_z = 2.00$ mm



(a) **(b)**

Fig. 4 Variation of intensity of edge recession i_ρ (μm/m) at different values of feed per insert f_z: **a** $f_z = 0.50$ mm, **b** $f_z = 2.00$ mm

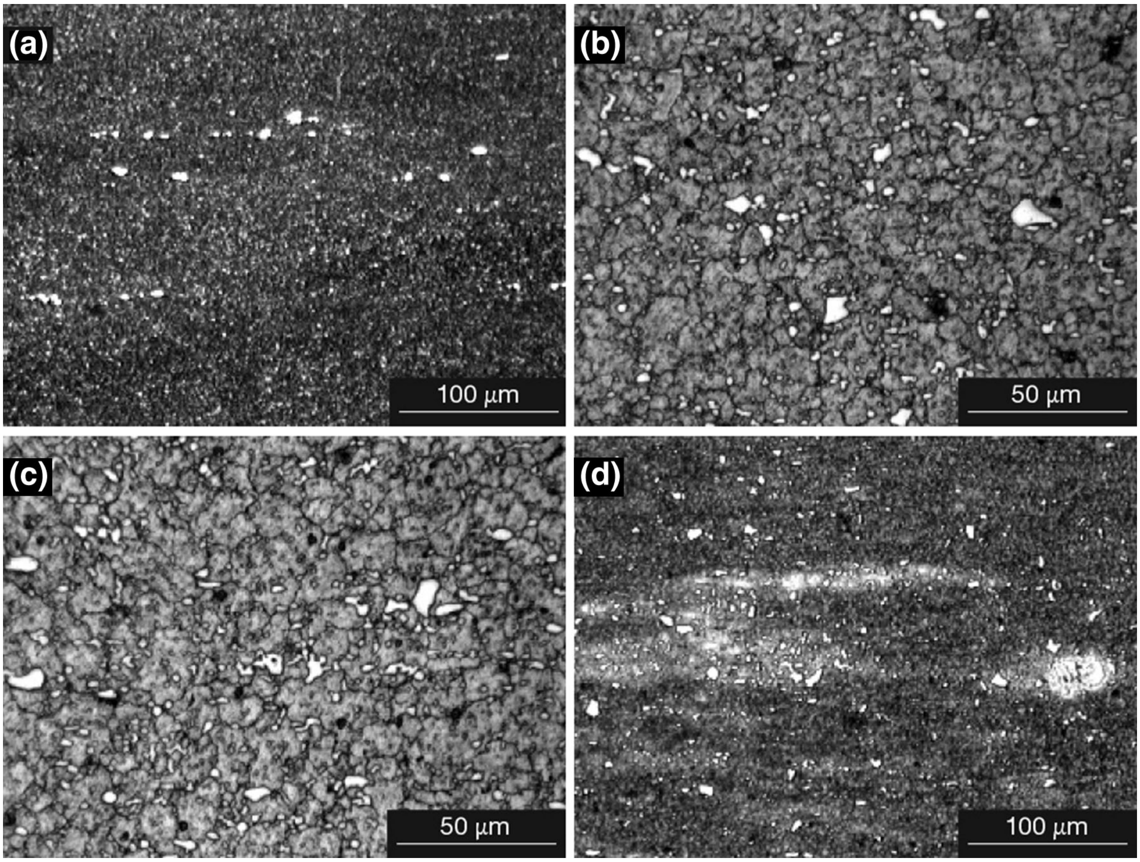


Fig. 5 Image of microstructure: **a** tool no. 1, **b** tool no. 2, **c** tool no. 3, **d** tool no. 4

Higher content of retained austenite presents in these segregation zones, showing that tempering process was incomplete; however, it did not affect wear resistance of tool—wear resistance of tool no. 4 is the highest. It is possible to maintain that regimes of heat treatment process influence wear behaviour of tools, but it was not studied in this research.

While evaluating influence of feed per insert on cutting edge radius, it is estimated that increasing the values of feed per insert radius of cutting edges increases as well. It is possible to set few periods in which wear process progresses according to different pattern. Firstly, influence of feed per insert is very low in the cutting length until 200 m. Cutting edge radius increases approximately in 9.76%, when feed per insert increases from 0.5 to 1.00 mm for tool no. 1 (Figs. 6, 7); comparing feed rates 1.00 and 1.50 mm increment of radius makes up 5.90%; the lowest different is observed between the highest feeds per insert—5.04%. Results of intensity of edge recession i_ρ prove all the assumptions (Fig. 8).

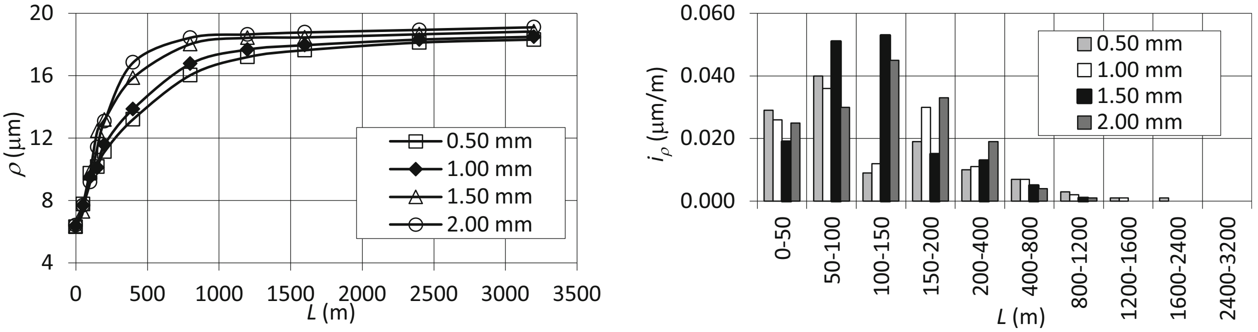


Fig. 6 Influence of feed per insert f_z (mm) on cutting edge radius ρ (μm) and on the intensity of edge recession i_ρ (μm/m) of tool no. 1

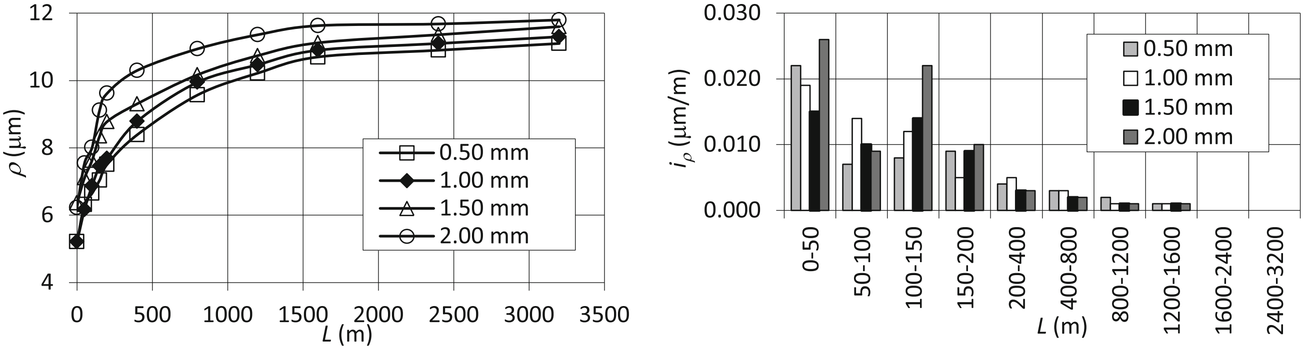
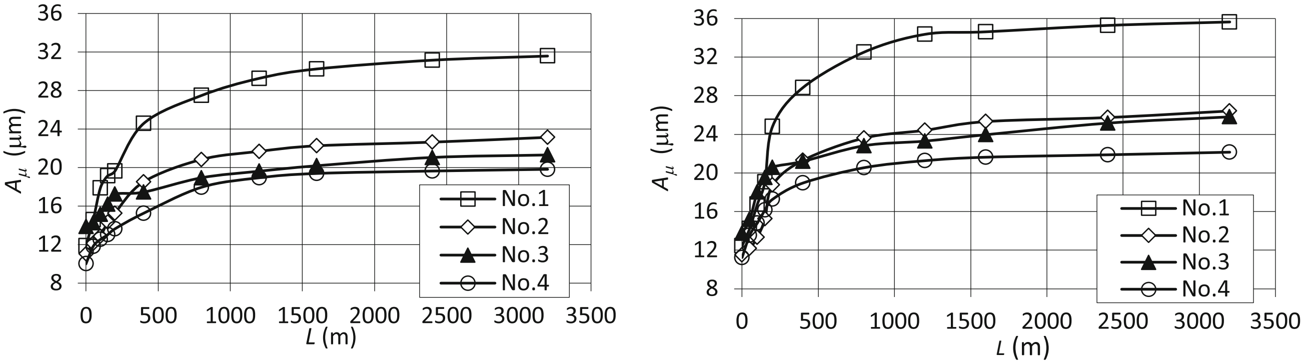


Fig. 7 Influence of feed per insert f_z (mm) on cutting edge radius ρ (μm) and on the intensity of edge recession i_ρ (μm/m) of tool no. 4



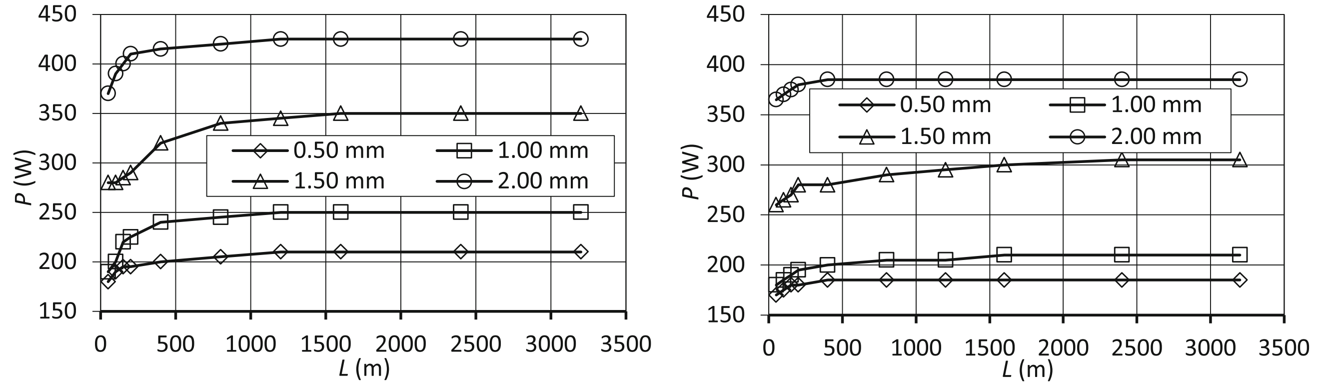
(a) **(b)**

Fig. 8 Influence of feed per insert on edge recession A_μ (μm): **a** $f_z = 0.50$ mm, **b** $f_z = 2.00$ mm

Obtained results prove the statements of cutting theory: on increasing average thickness of chip in wood milling process, edges of tool wear out more intensively [19, 24]. It is estimated that when chip thickness is lower, clearance surface of tool wears more intensively, influence of frictional force which acts to the rake surface is negligible, because contact sliding path of clearance surface is bigger than contact of rake surface. On increasing the thickness of chip, friction force and contact length increase.

The highest values of cutting power P and intensity of variation of cutting power coefficient i_p are achieved testing toll no. 1; such a tendency is seen for all feeds per insert (Fig. 9).

In the first period of milling until 200 m of cutting length edges of all tools undergo intensive crumbling of edges, therefore cutting power increases in average by 20 W. This period gives the highest increment in cutting edge radius and the intensity of edge recession. Next period of milling from 200 until 400 m shows stable process, because edges of all tools decrease gradually from crumbling wear to low wear phase. Not linear increment of cutting power is observed in the cutting length 400–800 m;



(a) **(b)**

Fig. 9 Influence of feed per insert f_z (mm) on cutting power *P* (W): **a** tool no. 1, **b** tool no. 4

edges of tools reach uniform wear (no crumbling of edges) phase. Section from 800 to 1600 m highlights slight but linear increment of cutting power. Difference of cutting power in the 1600 m of cutting length when feed per insert 0.50 mm: nos. 1 and 2—7.14%, nos. 1 and 3—9.52%, the highest difference nos. 1 and 4—11.9%. When increased feed per insert until 2.00 mm difference of cutting power has other values: nos. 1 and 2—4.71%, nos. 1 and 3—8.24%, the highest difference nos. 1 and 4—9.41%. These results prove that all milling tools after 1600 m of cutting length move to the monotonic phase of wear [25]. The last period tested in this study (1600–3200 m) shows monotonic wear; values are slightly increased for every feed per insert.

Conclusion

In this study, the technical characteristics of four standard tools from different suppliers have been studied by means of cutting edge radius, edge recession, cutting power, feed per insert. It is shown that chemical composition of tool material and heat treatment schedule has great impact on the tool edge wear. The highest wear resistance was shown testing tools made of CT01M-LA2 steel (no. 4); tools made of high-alloyed tool steel 8X6HФT (no. 1) have presented the highest cutting edge radius and edge recession in each type of test as compared with other tools made of high-speed tool steels Z80WCV 18-04-01/18-0-1 and HS 18-0-1 (nos. 2 and 3), respectively. High-speed tool steels possess more alloying elements, which increases hardness, strength and wear resistance of tools.

This study revealed that wear of tool edges is more intensive increasing feed per insert from 0.5 to 2.00 mm: inverse dependence was defined as compared with influence of cutting speed. It is determined that increasing feed per one insert cutting power and cutting edge radius increases as well.

Based on the microstructural, chemical, mechanical analysis and wear performance of tools, high speed tool steel CT01M-LA2 (tool no. 4) was chosen to be the most suitable steel among those tested for making of oak wood cutting tool.

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