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ORIGINAL ARTICLE

Effect of tool material on tool wear and delamination during machining of particleboard

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Abstract The tool material and the parameters of machining are the main conditions which decide the quality of particleboard surface. The objective of the study was to investigate the wear of a carbide cemented bit and high-speed steel bit during machining of melamine-faced particleboard. Analysis of variance (ANOVA) was implemented to find the significance of the effect of machining parameters and tool wear on the value of the delamination factor A_{del}. The delamination factor A_{del} is defined as the ratio of area of delamination (mm^2) to the measured length of the test piece (cm). To determine the durability of the cutting tool a geometric criterion was adopted, i.e., maximum wear of the tool flank. We observed a clear impact of cutting speed on the length of the tool life. This relation was manifested as a decrease in the tool life with increasing cutting speed. It was also found that a reduction in the cutting speed increases the area of delamination, leading to an increase in the value of the A_{del} factor. It was especially visible for higher values of tool wear. In the case of feed per tooth we observed no clear effect on intensifying the delamination phenomenon.

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Introduction

Particleboard is made up of wood chips bound together with resin and pressed into a flat, usually rectangular, shape. A synthetic resin is added, usually urea formaldehyde, to hold the chips together and increase the strength of the finished product. Because of their workability, dimensional stability and surface properties, particleboards are often used in industries, particularly in the furniture industry. In the literature, drilling and milling of wood-based materials have not received much attention (e.g., [1–4]) whereas the process of drilling and milling of metals and composites has been intensively studied [5, 6]. Drilling is the major operation during final assembly of particleboard, where fasteners are used to join everything together to achieve the final shape of the product [7, 8].

Chen et al. [9] analysed the density distribution characteristics of the four most commonly used wood-based panels. They concluded that MDF and particleboard panels were more uniform than oriented strand board and plywood panels. The surface roughness of particleboard is greatly influenced by the raw material type, board density, and pressure and shelling ratio [10]. Gaitonde et al. [11] concluded that with an increase in feed rate, the delamination factor increases; and it decreases at higher cutting speeds during the drilling of wood panels. From the experiments performed by Mercy et al. [12], it is clear that delamination increases along with feed and drill diameter, whereas it decreases with an increase in speed.

Mathew et al. [13] attempted to develop a mathematical model that can correctly predict the critical value of the thrust force in drilling composite laminates, which assures a minimal delamination. The mathematical model was validated using the results obtained in experimental studies. The analysis showed high correlation coefficient between the mathematical model and their research.

Signals of thrust force and the cutting torque are highly correlated with the quality of the products. There are many workers who deal with these very important indirect wear factors. Some studies, for example, El-Sonbaty et al. [14] or Khashaba et al. [15] take into account both the measurement of thrust force and cutting torque. On the other hand, others deal only with the thrust force, as Abrão et al. [16]. The effect of various parameters on values of cutting torque and thrust force, with respect to the composite materials is discussed by Davim et al. [17].

Modelling and experimental analysis of the orthogonal cutting mechanics of MDF are performed by Dippon et al. [18]. The experimental results showed that the friction on the rake face is rather small, and the pressure exerted by the uncut chip on the rake face mainly dominates the force on the rake face. The proposed cutting constants can be used to predict the cutting forces in machining MDF with tools having complex geometry such as router bits.

In contrast, extensive studies have been related to the construction of drill bits that were made of high-speed steel (HSS) and cemented carbide. The results obtained by Kaczorowski et al. [19] prove the possibility to apply carbon-based coatings to the mechanical machining of wood-based materials, in particular, in the treatment of non-laminated particleboards.

Tool life is the time of the blade cutting until it is blunt, i.e., reaching the maximum permissible value of specified wear or to catastrophic tool failure. Due to the mechanical overstress the breaking occurs over a substantial portion of the cutting edge. This phenomenon is called a catastrophic dull blade. Changes in geometry must be understood, which can be associated with chipping and changes due to the heat, blade deformation and also the chemical action of workpiece [20, 21]. Statistical regression was employed by Iskra et al. [22] to establish relationships between the signals from the cutting zone and the actual cutting depth and surface roughness.

An analysis of all known aspects of the correlation between the tool wear and cutting resistances has been carried out by many authors, e.g., Scholz et al. [23] and Cuppini et al. [24], but most well-known studies are based on tool wear during machining of metals. Prickett et al. [25] conducted a review of previously used methods for assessing the wear and the damage of the tool edge. They reviewed the use of artificial intelligence to make decisions about the state of the tool. Mankova et al. [26] presented an indirect method of determining the wear of the cutting tool by evaluating the signals of cutting force. The method can be used to assess the state of tools. Bouzakis and Koutoupas [27] developed a novel procedure that can be used to monitor the mechanical strength properties of particleboards under production conditions. The bending and indentation tests were used to determine particleboards' mechanical strength critical stresses and their correlation to the specific cutting force in milling.

In this article, we present the results of investigations of the delamination of melamine-faced particleboard during milling. We also investigated the effect of the cutting speed and feed per tooth on the value of the force parameters of the cutting process, and the effect of tool wear on the value of the delamination factor. Furthermore, the economical cutting speed and the cutting speed corresponding to the maximum efficiency of the milling process were evaluated. To determine the durability of the cutting tool a geometric criterion was used. In our investigations we tested two bits, one made of cemented carbide and the other of HSS.

Materials and methods

The milling process experiments were carried out using a high-speed steel bit of 14 mm diameter (Fig. 1a) and cemented carbide shank-type bit of 12 mm (Fig. 1b).

Tests were carried out with a standard CNC Busellato Jet 100 machining centre. The selected physical and mechanical properties of typical industrial and melamine-faced 18 mm thick particleboard determined according to suitable standards are listed in Table 1.

As a wear criterion, the maximum wear of the tool flank VB_{max} was adopted. In accordance with ISO 8688-1:1996 [32], the value VB_{max} = 1 mm was adopted as the limit value for this wear factor in the case of high-speed steel tools. For the cemented carbide the value

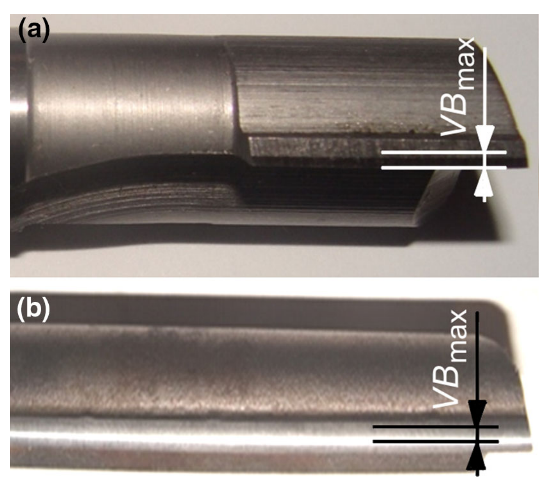

Fig. 1 Milling tools: **a** high-speed steel bit and **b** cemented carbide shank-type bit

Table 1 Selected physical and mechanical properties of melamine-faced particleboard

Parameter	Density (kg/m^3)	Surface soundness (N/mm^2)	Transverse tensile strength (N/mm^2)	Bending strength (N/mm^2)	Bending elasticity modulus (N/mm^2)
Value	670	1.3	0.43	16.39	2453
Standard of testing mehod	EN 323 [28]	EN 311 [29]	EN 319 [30]	EN 310 [31]	EN 310 [31]

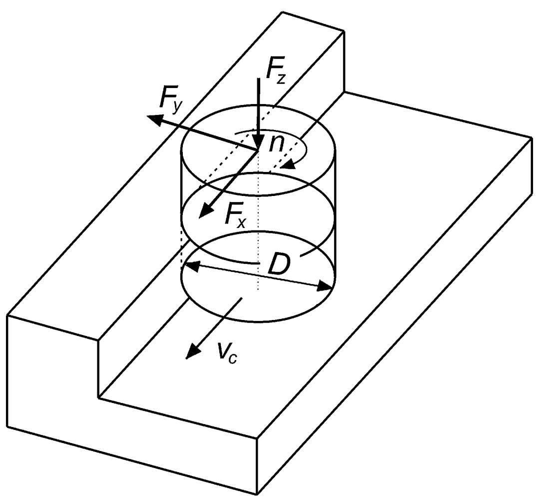

Fig. 2 Distribution of force components in the milling process

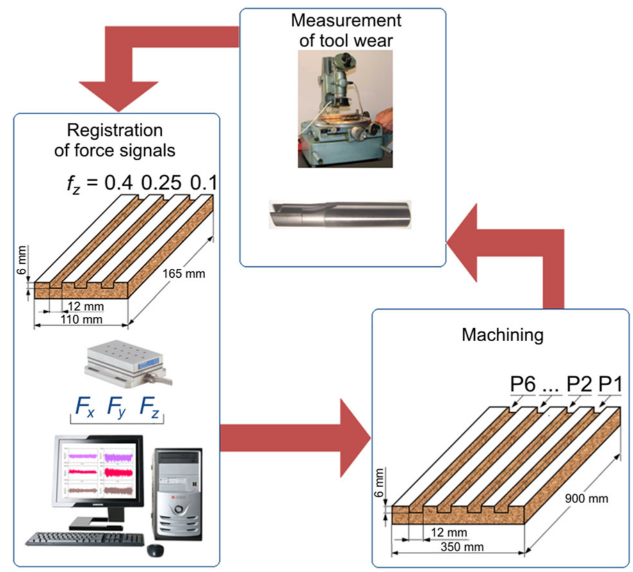

Fig. 3 Research method

$VB_{max} = 0.2$ mm was assumed. In addition, it was decided to determine the influence of the basic cutting parameters (cutting speed, feed rate) on the particleboard surface quality and the value of the signals of forces occurring in the machining process, i.e., F_x, F_y, F_z (Fig. 2).

The values of the cutting parameters corresponded to medium quality machining carried out with cutting speeds corresponding to the expected tool life periods. Durability tests were performed for five different cutting speeds v_c (4.4, 6.59, 8.79, 10.99, 13.19 m/s) with three levels of feed per tooth (0.1, 0.25, 0.4 mm/tooth), depth of cut $a_p = 6$ - mm and the width of milling $a_e = 14$ mm. We considered five rotational speeds of the milling cutter n (6000, 9000, 12000, 15000, 18000 rev/min). The number of repetitions of each test was three. The values of the wear factor of the cutting tool were measured using a laboratory microscope, and then the values of the cutting forces were recorded on the measuring platform with three adopted values of feed per tooth. Before the first milling operation using the new tool, the registration of force signals during one pass P1 (Fig. 3) was done. Then, after the end of each operation consisting of six passes (P1–P6) the tool wear was measured. In the experiments we used a Kistler type 9601A3 piezoelectric sensor and a 5034A3 charge-sensitive preamplifier. The sensor was placed on a multi-component force plate. The signals of the cutting forces via a charge preamplifier were transferred to the analogue-to-digital NI PCI-6034 converter installed in a personal computer and recorded with a sampling rate of 50 kHz.

The results of experiments were analysed using our own computer programme in LabView programming language. This programme allowed us to evaluate the measured values of the recorded signal strength at selected periods of time. We took into account the average value of the measurement from the cut at 0.1 s after the signal value exceeded the initial force value. As a measure of the signals we decided to determine the root-mean-square (RMS) value of the signals of both forces, F_x and F_y.

Economical and efficient wood machining

Following Jemielniak [33], who described in detail the methods for analysis of the machining process, the tool life that ensures the maximum machining efficiency during the milling process is defined below. The unit processing efficiency q is defined as the number of operations performed per unit time. It is the inverse of the cycle time t_j:

$$q = \frac{1}{t_j} \tag{1}$$

$$t_j = \frac{L}{n} + \frac{t_z}{n_T} + t_p \tag{2}$$

where: t_z the time of tool removal, t_p auxiliary time, n_T the number of operations at the period of tool life under the cut, L the length of pass, N the rotational speed of tool.

We look for a minimum cycle time, which corresponds to the maximum efficiency. Taking into consideration that rotational speed of tool n:

$$n = \frac{1000 \cdot v_c}{\pi \cdot D} \tag{3}$$

and cutting speed v_c is:

$$v_c = C_v \cdot T^{1/k} \tag{4}$$

we obtain the formula for determination machining time t_m:

$$t_m = \frac{\pi \cdot D \cdot L}{1000f \cdot C_v} T^{-1/k} \tag{5}$$

where C_v the cutting speed corresponding to the tool life $T = 1$, D the bit diameter, f feed rate, k a slope of a linear relationship between tool life T and cutting speed v_c developed by Taylor [34] in the double logarithmic coordinate system.

To simplify the Eq. (5) we can introduce new parameter C_m:

$$C_m = \frac{\pi \cdot D \cdot L}{1000f \cdot C_v} \tag{6}$$

Then the machining time t_m takes the form:

$$t_m = C_m \cdot T^{-1/k} \tag{7}$$

Then the number of operations attributable to the tool life n_T can be defined as:

$$n_T = \frac{T}{t_m} = \frac{1}{C_m} T^{1+1/k} \tag{8}$$

The cycle time t_j can be defined as:

$$t_j = C_m \cdot T^{-1/k} + C_m \cdot T^{-1-1/k} \cdot t_z + t_p \tag{9}$$

The derivative of the cycle time t_j in relation to tool life takes the form of:

$$\frac{\partial t_j}{\partial T} = -\frac{1}{k} \cdot C_m \cdot T^{-1/k-1} + \left(-1 - \frac{1}{k}\right) C_m \cdot T^{-2-1/k} \cdot t_z \tag{10}$$

The value of this derivative is equal to 0 for $T = T_q$, and T_q is the tool life of the highest efficiency. Dividing both sides of Eq. (10) by $C_m \cdot T_q^{-2-1/k}$ we obtain:

$$-\frac{1}{k} \cdot T_q + \left(-1 - \frac{1}{k}\right) t_z = 0 \tag{11}$$

and finally

$$T_q = (-k - 1) t_z \tag{12}$$

Tool life period T_q corresponds to the cutting speed at the highest efficiency v_q:

$$v_q = C_v \cdot T_q^{1/k} \tag{13}$$

The cost of wood machining operations is equal to:

$$K = t_m \cdot K_O + t_z \frac{K_O}{n_T} + \frac{K_N}{n_T} \tag{14}$$

where: K_O the cost of woodworking machine, maintenance and overheads, and K_N the cost of a tool per cutting edge.

Substituting Eq. (14) into Eqs. (5) and (8), we obtain:

$$K = C_m \cdot T^{-1/k} \cdot K_O + (t_z \cdot K_O + K_N) C_m \cdot T^{-1-1/k} \tag{15}$$

We look for a minimum cost as a function of tool life. After differentiation of Eq. (15) with respect to T we obtain:

$$\frac{\partial K}{\partial T} = -\frac{1}{k} C_m \cdot T^{-1-1/k} \cdot K_O + \left(-\frac{1}{k} - 1\right) C_m (t_z \cdot K_O + K_N) T^{-2-1/k} \tag{16}$$

This derivative is 0 for $T = T_e$. Therefore, comparing Eq. (16) to zero and dividing the resulting equation by $K_O \cdot C_m \cdot T_e^{-2-1/k}$ we obtain:

$$-\frac{1}{k} \cdot T_e + \left(-\frac{1}{k} - 1\right) \left(t_z + \frac{K_N}{K_O}\right) = 0 \tag{17}$$

and then the economical cutting edge life T_e:

$$T_e = (-k - 1) \left(t_z + \frac{K_N}{K_O}\right) \tag{18}$$

The regular cutting speed that allows us to obtain the tool life T_e is an economical cutting speed v_e:

$$v_e = C_v \cdot T_e^{1/k} \tag{19}$$

Results and discussion

Economical and efficient wood machining

Mathematical formulae have been derived in "Economical and efficient wood machining" to determine efficient and economical and cutting speed for a machining operation, given that the various time and cost components of the operation are known. On the basis of durability tests of the bits, it was decided to launch a study to determine the economical and efficient cutting speeds v_e and v_q, respectively. Figure 4 shows in a double logarithmic coordinate system the effect of the cutting speed on tool life in the five durability tests carried out with different cutting speeds. Based on the approximation line, the values of the parameters in Taylor's equation which are necessary to evaluate the values of cutting speeds v_q (Eq. 13) and v_e (Eq. 19) were determined:

– high-speed steel bit: $k = -1.57$, $C_v = 1778$,
– cemented carbide bit: $k = -3.63$, $C_v = 1047$.

To determine the cutting speed corresponding to the maximum efficiency v_q, the tool life corresponding to the highest efficiency T_q, economical cutting speed v_e and economical cutting edge life T_e (Table 2), we had to assume the values of constants in Eqs. 12 and 18: t_z, K_O, K_N. The values of the parameters were assumed as follows: t_z 2 min, K_O 35 EUR/h, K_N 12 EUR. According to Eq. (18), the significant parameter that influenced the economical cutting speed v_e is the ratio of K_N to K_O cost. So, if the cost of woodworking machine, maintenance and overheads K_O decreases, then the economical cutting edge life T_e increases.

For both tool materials the value of the economical cutting speed is obtainable on a standard drilling machine, and the computational speed for the maximum efficiency exceeds the speed range of known milling machines used in wood drilling operations. Furthermore, the tool life corresponding to the highest efficiency T_q for high-speed steel tool was more than 10 times smaller than the economical cutting edge life T_e. In the case of the cemented carbide bit the tool life corresponding to the highest efficiency was more than 20 times smaller than the economical cutting edge life T_e.

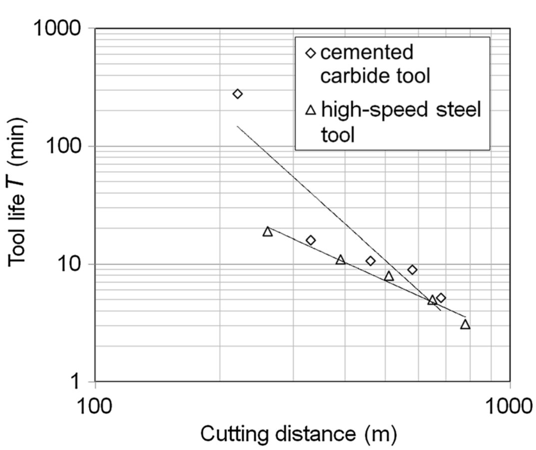

Fig. 4 Influence of cutting speed on the tool life

Tool life

We observed a clear impact of cutting speed on the length of the tool life and this relation is manifested as a decrease in the tool life with increasing cutting speed. The milling cutter made of high-speed steel machining at $n = 18000$ rev/min after a cutting distance of about 290 m reached the assumed value of tool flank wear $VB_{max} = 1$ mm, and the allowable tool wear of the milling cutter operated at high rotational speed $n = 6000$ rev/min was reached after about 1000 m (Fig. 5). The assumed value of tool wear VB_{max} for the cemented carbide bit was smaller than in the case of the high-speed steel tool so the cutting distances required to reach the tool wear $VB_{max} = 0.2$ mm were lower. Moreover, in the initial period of tool operation ($l_s = 0$–20 m) with increasing cutting speeds a fast increase in tool wear was observed. In the case of the lowest rotational speed $n = 6000$ rev/min the maximal value of tool wear was reached after a distance of only 37 m. The permissible value of cutting distance to reach assumed tool wear value of cemented carbide bit machining at $n = 18000$ rev/min was 523 m. Considering the machining at the highest rotational speed, the cutting distance of cemented carbide bit to reach the assumed VB_{max} value was about twice as small as in the case of the high-speed steel bit. Simultaneously, the assumed value of cemented carbide tool wear was five times smaller compared with the high-speed steel bit. As Porankiewicz et al. found [35], the wear of the cutting of HSS is similar to that reported for cemented carbide. The use of cemented carbide tools might give even better results; however, large accidental chipping greatly reduces the efficiency [36]. Plastov [37] found that the quality of milling of laminated particleboards decreases with a regular tendency with tool blunting progression.

Table 2 Parameters of efficient and economical wood machining

Tool material	Woodworking model	Cutting speed v_c (m/s)	Rotational speed, n (rev/min)	Tool life T_q, T_e (min)
High-speed steel	Efficient		>18000	$T_q = 1.14$
	Economic	5.92	11309	$T_e = 12.54$
Cemented carbide	Efficient		>18000	$T_q = 5.26$
	Economic	4.7	9123	$T_e = 110.46$

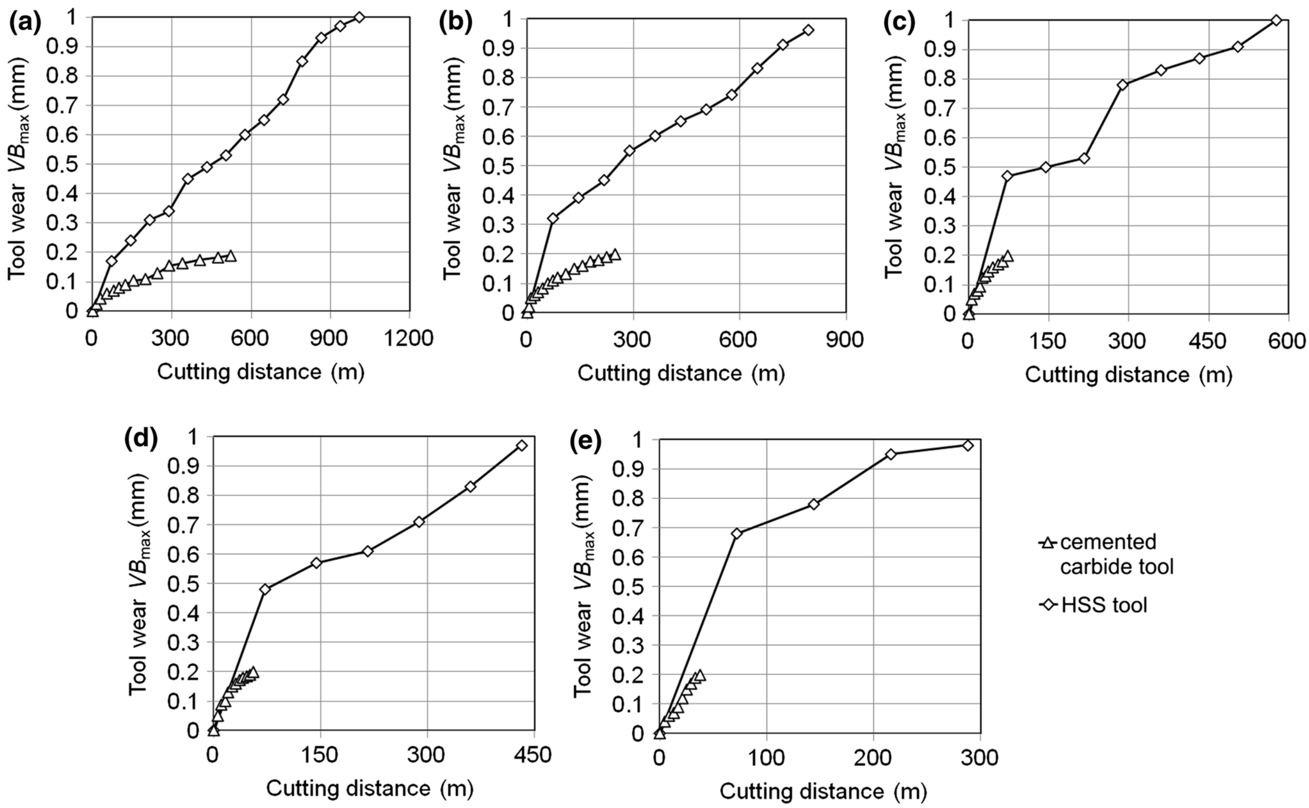

Fig. 5 Variation of tool wear as a function of cutting distance: **a** $n = 6000$ rev/min, **b** $n = 9000$ rev/min, **c** $n = 12000$ rev/min, **d** $n = 15000$ rev/min, **e** $n = 18000$ rev/min; $f_z = 0.25$ mm/tooth

ANOVA analysis

Multivariate analysis of variance (ANOVA) allows us to check the significance of the impact of a few independent variables on the dependent variable. It was reported that the ANOVA method is suitable to determine the contribution of process parameters to the measured feature of a product [38]. Furthermore, it makes it possible to take into account the synergistic effect of the product of many variables in the statistical model. Taking into account the adopted level of significance $p = 0.05$, the statistical significance of individual groups of variables and individual variables were determined using the Statistica programme. The significance of the influence of the two controlled parameters f_z and v_c on the change of force parameters of the particleboard milling process is described. The change in the tool wear during the operation is a continuous process, so the analysis assumes the following ranges of changes in the high-speed steel tool wear: $VB_1 = 0$–0.04 mm, $VB_2 = 0.405$–0.7 mm and $VB_3 = 0.705$–1 mm. In the case of the cemented carbide bit the following ranges of changes in the tool wear were assumed: $VB_1 = 0$–0.05 -mm, $VB_2 = 0.055$–0.1 mm, $VB_3 = 0.105$–0.15 mm, and $VB_4 = 0.155$–0.2 mm. The results of analysis for both bit materials (Tables 3, 4) allow us to reject, at the significance level $p = 0.000$, the hypothesis about the lack of the effect of parameters VB_{max}, and v_c on the value of the signal of force F_x. Statistically significant interactions between the analysed factors were observed to occur: interaction between the values of force signals and the products of factors VB_{max} and f_z (at $p = 0.005$), and VB_{max} and v_c (at $p = 0.000$). Statistically significant interactions between parameters VB_{max} and f_z (at $p = 0.027$), and VB_{max} and v_c (at $p = 0.042$) were observed during machining using the cemented carbide tool.

There was a strong correlation between the value of the signal of force F_y and the values of parameters VB_{max} and v_c at $p = 0.000$, and the value of the feed f_z at significance level $p = 0.004$. The two-factor formulas $f_z \cdot v_c$, and $VB_{max} \cdot v_c$ contributed important predictive information to the analysis of variance at the level of significance $p = 0.013$ and $p = 0.000$, respectively. The character of the effect of feed per tooth f_z and wear VB_{max} on the root-mean-square value of the signals F_x and F_z is clear in the range of values of these parameters applied in the study, i.e., increase in the value of these parameters resulted in an increase of the root-mean-square values of the F_x (Fig. 6) and F_y signals (Fig. 7). Gaitonde et al. [39] found that less cutting force is required to shear the material, resulting in minimum delamination. Palmqvist et al. [40] reported a very significant influence of normal force changes during rotational machining. Furthermore, according to Kowaluk et al. [41], the basic parameter that helps to diagnose effectively the milling operation is the normal force to the feed direction, which provides a very responsive sensor for edge geometrical changes.

Table 3 Significance of the influence of cutting parameters and high-speed steel tool wear on the value of signals of force components F_x and F_y

Variables	Force component F_x		Force component F_y	
	p value	Significance	p value	Significance
f_z	0.000	Significant	0.004	Not significant
VB_{max}	0.000	Significant	0.000	Significant
v_c	0.000	Significant	0.000	Significant
$f_z \cdot VB_{max}$	0.005	Significant	0.135	Not significant
$f_z \cdot v_c$	0.656	Not significant	0.013	Not significant
$VB_{max} \cdot v_c$	0.000	Significant	0.000	Significant
$f_z \cdot VB_{max} \cdot v_c$	0.997	Not significant	0.886	Not significant

Table 4 Significance of influence of cutting parameters and cemented carbide tool wear on value of signals of force components F_x and F_y

Variables	Force component F_x		Force component F_y	
	p value	Significance	p value	Significance
f_z	0.000	Significant	0.000	Significant
VB_{max}	0.000	Significant	0.000	Significant
v_c	0.000	Significant	0.000	Significant
$f_z \cdot VB_{max}$	0.027	Not significant	0.096	Not significant
$f_z \cdot v_c$	0.000	Significant	0.000	Significant
$VB_{max} \cdot v_c$	0.042	Not significant	0.014	Not significant
$f_z \cdot VB_{max} \cdot v_c$	0.006	Not significant	0.276	Not significant

For the bit made of HSS, in the range of the VB_{max} wear of 0-0.4 mm there was no visible effect of tool wear on the value of force signals F_x and F_y (Figs. 8a, 9a). Increasing the tool wear above the value of 0.4 mm increased the effect of the tool wear on the value of both analysed force signals. During machining using the cemented carbide tool there was an effect of the feed on the value of cutting forces (Figs. 8b, 9b). Similar dependences were observed for all analysed cutting speeds. The largest increase in signal amplitude related to the increase of tool flank wear was observed for the force component F_y.

Delamination factor

The quality of the edge of the melamine-faced particleboard deteriorated as expected with increase in tool wear, as reported by other authors (e.g., [10, 33, 42]). Based on the digital images of the machined surface obtained during the registration process of digital signals of forces, an image analysis of the machined surface was carried out. The digital images were subjected to digital treatment with the Vision Assistant application in the LabView environment. The delamination factor A_{del} measured on the length L_p of a test piece equal to 165 mm was determined according to the formula:

$$A_{del} = \frac{S_{del}}{L_p} \tag{20}$$

where S_{del} area of delamination (mm^2), L_p measured length of the test piece (cm).

Figure 10 presents the relationship between the delamination factor A_{del} and the tool wear VB_{max} for both bit materials. It is observed that there is not only a clear relationship between the tool wear VB_{max} and the

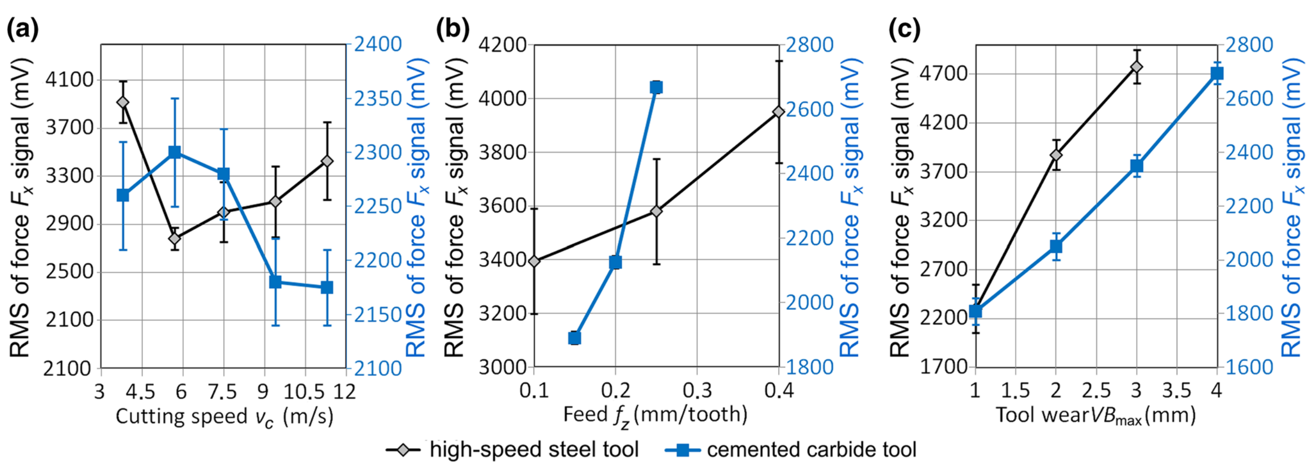

Fig. 6 Effect of cutting parameters v_c (**a**) and feed f_z (**b**), and tool wear (**c**) on the value of root-mean-square (RMS) of signals of force F_x

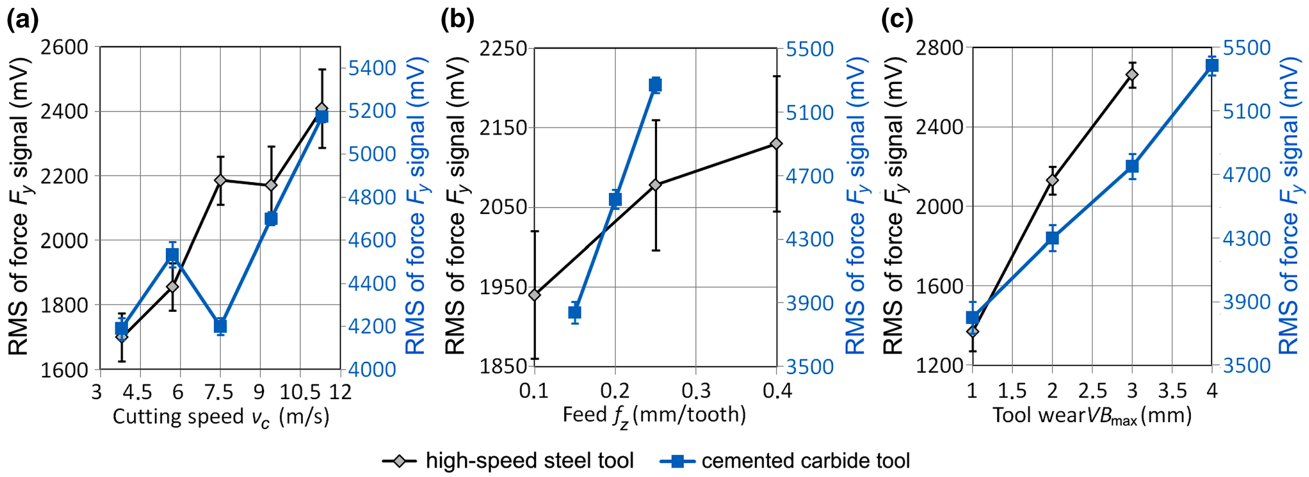

Fig. 7 Effect of cutting parameters v_c (**a**) and feed f_z (**b**), and tool wear (**c**) on the value of root-mean-square (RMS) of signals of force F_y

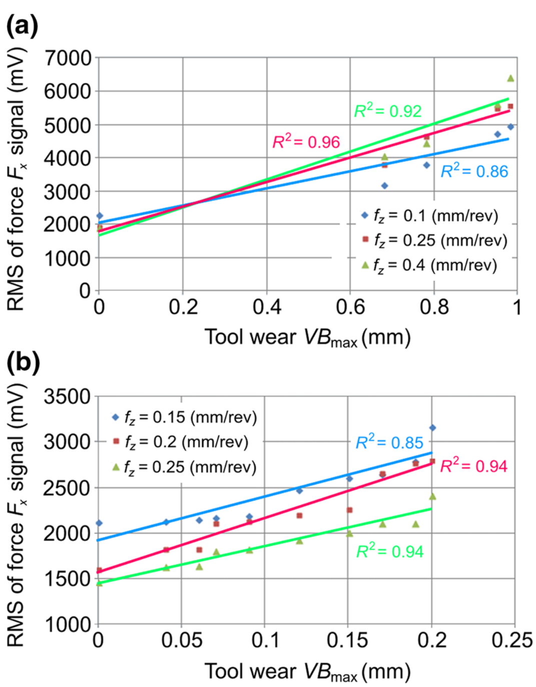

Fig. 8 Dependence of the root-mean-square (RMS) of force F_x signal vs. tool wear at $v_c = 13.9$ m/s for high-speed steel tool (**a**) and cemented carbide tool (**b**)

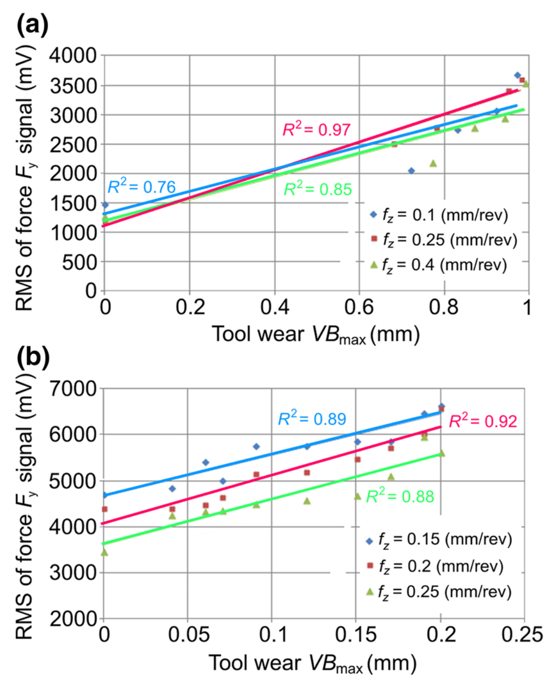

Fig. 9 Dependence of the root-mean-square (RMS) of force F_y signal vs. tool wear at $v_c = 13.9$ m/s for high-speed steel tool (**a**) and cemented carbide tool (**b**)

delamination factor A_{del}; a reduction in the cutting speed also increases the area of delamination, leading to an increase in the value of the A_{del} factor. It was especially visible for larger values of tool wear. These findings agree with the results of Mercy et al. [7]. The same conclusion was made by Davim et al. [43], who found that by employing higher cutting speed it is possible to reduce the delamination tendency in drilling. Similar results were found by Gaitonde et al. [44]; the surface roughness of MDF during milling can be optimised with lower feed rate and higher cutting speeds. In the case of feed per tooth f_z, we observed no clear effect on intensifying the delamination phenomenon of the particleboard edge. This conclusion does not agree with the results of investigations carried out by Davim et al. [45], who studied the surface roughness change in milling the MDF in range of feed rate between 0.5 and 5 m/min. These authors found that the surface roughness increases with increasing feed rate. This does not mean, however, that the effect of the f_z parameter is negligible, because in our investigations the f_z value was limited to a specific range.

Results of the analysis of variance (Fig. 11) confirmed that the value of the tool wear significantly affects the process of delamination. Similar conclusions can be drawn in relation to the cutting speed's effect on the value of the delamination area S_{del} (at $p = 0.000$). Davim et al. [46] concluded that an increase of cutting velocity is the main parameter that influences the decreasing of the delamination factor. Gaitonde et al. [44] observed that high-speed cutting plays a major role in reducing damage during drilling of carbon fibre-reinforced composites. The findings of Davim et al. [17] also suggest that delamination increases with feed rate and cutting speed for both tool materials, HSS and cemented carbide. To summarise, a change in both the cutting speed and tool wear has a statistically significant effect on the area of delamination. However, a change in the feed per tooth has no significant effect ($p = 0.092$). There was no statistically significant synergistic effect of the products of the analysed parameters on the value of the area of delamination.

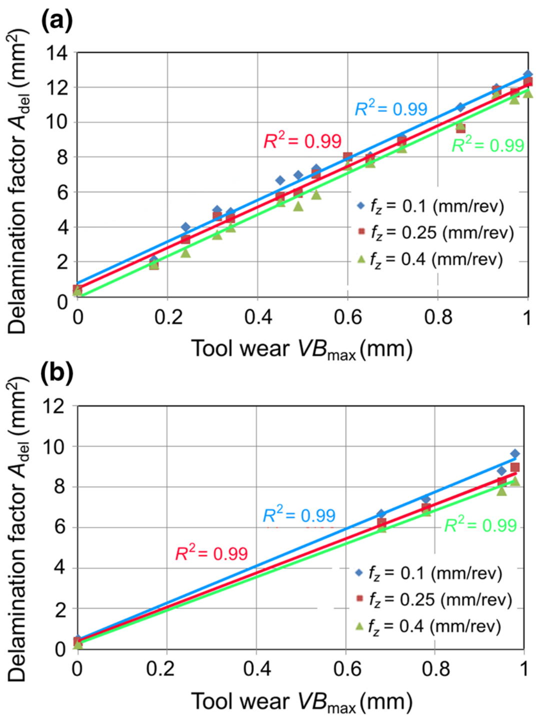

Fig. 10 Dependence of the delamination factor A_{del} vs. high-speed steel tool wear for cutting speeds: $v_c = 4.40$ m/s (**a**) and $v_c = 13.19$ m/s (**b**)

Conclusions

The experimental results allow us to draw the following conclusions:

1. For both tool materials economical cutting speed is obtainable on a standard drilling machine, and the computational speed for the maximum efficiency exceeds the speed range of known milling machines used in wood drilling operations. In the case of a cemented carbine bit the tool life corresponding to the highest efficiency was more than 20 times smaller than the economical cutting edge life T_e.
2. A clear impact of cutting speed on the length of tool life is manifested as a decrease in the tool life with increasing cutting speed. The assumed value of tool wear VB_{max} for a cemented carbide bit is smaller than for a high-speed steel tool so the cutting distances required to reach tool wear $VB_{max} = 0.2$ mm are lower. Considering the machining at the highest rotational speed, the required cutting distance of a cemented carbide bit to reach the assumed VB_{max} value is about twice as small as that of a high-speed steel bit.
3. Statistically significant effects of the analysed factors, e.g., tool wear, cutting speed and feed, on the value of the signal of force F_x were observed.

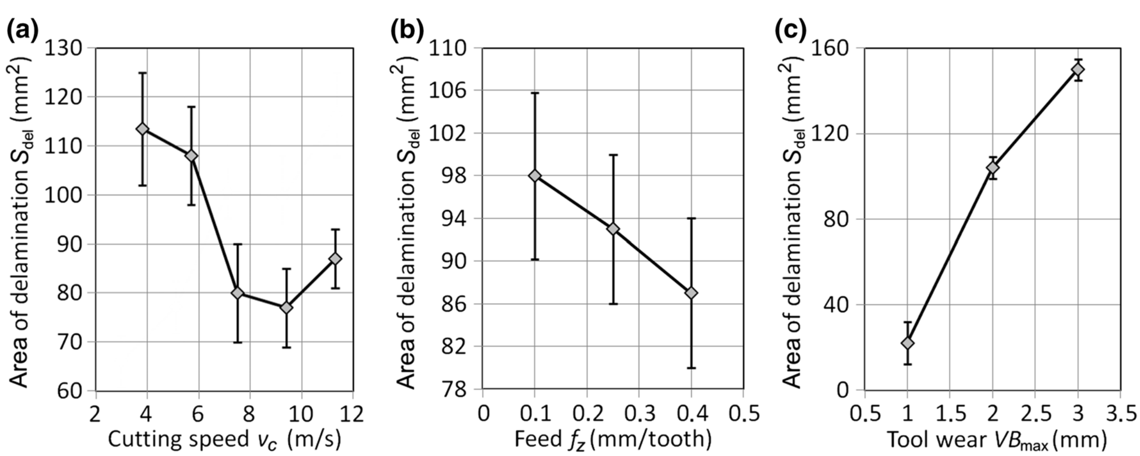

Fig. 11 Influence of cutting speed v_c (**a**) and feed f_z (**b**), and tool wear (**c**) on the value of area of delamination for high-speed steel tool

4. For the bit made of high-speed steel, in the range of the VB_{max} wear of 0–0.4 mm there was no visible effect of tool wear on the value of F_x and F_y force signals. During machining using the cemented carbide tool there was an essential effect of the feed on the value of cutting forces. Similar dependences were observed for all analysed cutting speeds.
5. A reduction in the cutting speed increased the area of delamination, leading to an increase in the value of the Adel factor. It is especially visible for larger values of tool wear. In the case of feed per tooth f_z, we observed no clear effect on the delamination phenomenon of the particleboard.

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