

## Milling a chipboard with a high-speed steel tool

KRZYSZTOF SZWAJKA, JOANNA ZIELIŃSKA-SZWAJKA

Faculty of Mechanical Engineering and Technology, Rzeszow University of Technology

**Abstract:** *Milling a chipboard with a high-speed steel tool.* In the paper the results of investigations of wear of a high-speed steel double-bit mill during milling of melamine-faced chipboard are presented. Experimental investigations also identified the effect of the cutting speed and feed per tooth on the value of force parameters in the cutting process as well as on the value of the factor of the chipboard edge delamination. The significance of the effect of cutting process parameters and tool wear on the value of the delamination factor was determined using multivariate analysis of variance. Delamination is the main damage observed during the machining of chipboard. A statistical analysis of the experimental results indicates that the main parameters determining the degree of damage to the chipboard edges are the wear of the tool flank and the cutting speed. Furthermore, the economic cutting speed and the cutting speed corresponding to the maximum efficiency of the milling process are evaluated. The value of the economical cutting speed can be obtained on a standard CNC machine. The cutting speed that ensures the maximum efficiency exceeds the maximum cutting speed that it is possible to obtain on a standard CNC woodworking machine.

*Keywords:* milling, chipboard, tool life, delamination factor, tool wear

### INTRODUCTION

Wood materials in the form of chipboard, fibreboard and plywood are used predominantly in both the furniture and construction industry as insulation materials, windows and doors, floor elements and furniture frontages. In the construction industry an increase in the use of wood-based panels of type MDF (medium density fibreboard), HDF (high density fibre), chipboard and fibreboard is observed (Thoemen et al. 2010). Among the materials used in the furniture industry, as much as 90% of materials are wood-based panels. Multilayer wood-based materials are produced from wood particles of different sizes compressed under high temperature and pressure, using resins, mainly urea-formaldehyde, melamine and phenolic (Sari et al. 2013; Thoemen et al. 2010), as the adhesive.

The progressive loss of cutting properties of tools affects negatively the quality and accuracy of the machined surface. The degree of damage (delamination) depends on the method and type of machining, cutting parameters, bonds but mainly on the condition of the cutting tool (Faga and Senttineri 2006; Knorz et al. 2014; Porankiewicz et al. 2005). In the process of machining wood-based materials, the state of the cutting blade, described by its wear, is the most important factor that determines the accuracy and quality of machining (Jemielniak 2002; Porankiewicz 1993; Szwajka 2017). The tool wear must therefore be taken into account during its operation due to its significant impact on the efficiency and cost of machining. Porankiewicz et al. (2015) have investigated specific wear on the rake face made of sintered carbide cutting edge during milling of laminated wood. The mechanical properties of chipboard affect the consumption of carbide cemented tools (Porankiewicz 2003) and the value of the force parameters (Bouzakis et al. 1999; Kowaluk et al. 2009) during the milling process. Increasing the thrust force and cutting speed by changing the cutting parameters also accelerates the wear of the tool during machining of wood-based materials (Lin and Chen 1996; Valarmathi et al. 2013). In the analysis of cutting resistances during machining of wood materials, the density and the humidity (Baharoğlu et al. 2012) of a material are the most important factors, wherein an increase of humidity causes an increase of the cutting resistance. Lin and Chen (1996), when drilling a medium-density fibreboard, studied the effect of the cutting speed on the surface quality, the value of the thrust force and tool wear.

The intensification of the tool wear process leads to a rapid increase in thrust force and is caused mainly by an increase of cutting speed.

The most objective way to evaluate the wear of the tool is to measure the geometric parameters of wear (Jemielniak 2002; Laszewicz et al. 2013, Szwajka 2016). An example of such parameters is the wear observed at the tool flank or on the rake face of the blade (Szwajka and Górski 2006). According to Dippon et al. (2000), the friction on the tool rake face during orthogonal cutting of MDF boards is very small, while there is excessive wear on the tool flank.

Unfortunately, the measurement of geometric parameters of tool wear requires a break in the machining process, which in industrial conditions is troublesome and economically unjustified. Similarly to the metal machining process, the measurement of indirect wear indicators, i.e., changes in physical parameters due to wear (Jemielniak 2002), is used to diagnose the state of the tool and cutting process of wood materials. Monitoring of the cutting forces (Lin and Chen 1996; Porankiewicz 2003) and derivative parameters as well as acoustic emission (Jemielniak 2002) is the most commonly used method to measure the indirect wear indicators. An alternative to monitoring the wear of the blade during milling of chipboard can be a video analysis of changes in the geometry of the workpiece (Laszewicz et al. 2013). The most important criterion for assessing the quality of processing of wood-based materials is the state of the edge of the board (Laszewicz et al. 2013; Lin et al. 2006; Nemili et al. 2007; Palanikumar et al. 2009). The quality is assessed, on the one hand, on the basis of the damage to the laminate in the vicinity of the processing zone (Ramesh Babu and Pradhan 2007), and on the other hand, based on the bead of the particleboard edge (Büyüksari et al. 2010). Even one clearly visible chip in the laminate on the edge of the board leads to the board's rejection from the further production process, and simultaneously raises the total cost of production. Delamination is the main damage observed during machining of chipboard and is intensified with increasing tool wear (Capello 2004; Tsao and Hocheng 2007). For this reason, delamination is a main factor determining the quality of the chipboard surface. To determine the area of the damage (delamination) to the edge of the chipboard, commonly used indicators of delamination take into account the number of detachments (Lemaster et al. 2000), the width of the delamination (Bouzakis et al. 1999; Porankiewicz 1993), the diameter of the delamination (during drilling) (Chen 1997; Davim and Reis 2003a, Davim and Reis 2003b, Feito et al. 2014), or the surface area of the delamination (Górski and Wilkowski 2003; Romoli and Dini 2008). The quality of the edge of melamine-faced chipboard during circumferential milling has been studied by Porankiewicz (2003). The process of delamination of a chipboard may be limited by the use of lower feed rates (Gaitonde et al. 2008; Palanikumar et al. 2009) and an increase of the cutting speed (Mercy et al. 2014). In the literature, the milling of wood-based materials has not received much attention (e.g., Lin et al. 2006; Porankiewicz 1993; Semotiuk 2009; Szwajka and Górski 2006), while the process of drilling and milling of metals and composites has been intensively studied (Królczyk et al. 2013; Semotiuk 2009). One of the major issues in machining, not only of wood-based materials, is the selection of suitable cutting parameters. Due to the coincidence of the expectations of the best effects of machining, such as accuracy, cost and productivity, we must often fulfil quite contradictory requirements. For example, due to the need to ensure high precision of machining it is indicated to select small feed rates, but this results in a decrease of productivity. Put simply, it can be assumed that optimization of the machining process involves proper selection of the technological parameters of cutting: cutting depth, feed rate and cutting speed. The choice of value of these parameters must ensure that the required surface quality is obtained at the maximum possible efficiency of the processing. Research reported in the literature concerning the processing of wood materials devotes little attention to the effect of tool wear, feed rates and cutting speeds on the process of

delamination in the drilling and milling of wood-based materials. The investigations are often carried out with constant values of the cutting parameters, and thus do not include in a reliable way an interaction effect between the above-mentioned factors and the delamination factor. Taking into account the complexity of the problem of selecting the cutting conditions when machining wood-based materials and the lack of comprehensive research on the chipboard milling process, the paper presents the results of wear of a high-speed steel double-bit mill during milling of melamine-faced chipboard. Experimental studies also identified 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 blade wear on the value of the delamination factor. The significance of the effect of cutting process parameters and blade wear on the delamination factor value was determined using multivariate analysis of variance. Furthermore, the economical cutting speed and the cutting speed corresponding to the maximum efficiency of the milling process are evaluated.

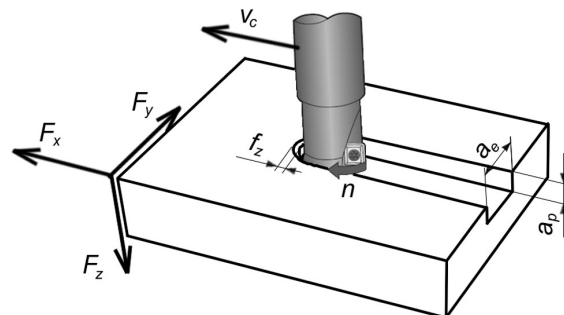
## MATERIALS AND METHODS

In the experiments a typical industrial and melamine-faced 18 mm thick chipboard was used. The selected physical and mechanical properties of the chipboard determined according to suitable standards are listed in Table 1.

**Table 1.** Selected physical and mechanical properties of melamine-faced chipboards used in the research

Parameter	Density [kg/m <sup>3</sup> ]	Surface soundness [N/mm <sup>2</sup> ]	Transverse tensile strength [N/mm <sup>2</sup> ]	Bending strength [N/mm <sup>2</sup> ]	Bending elasticity modulus [N/mm <sup>2</sup> ]
Melamine-faced chipboard	670	1.3	0.43	16.39	2453
Standard of testing method	EN 323	EN 311	EN 319	EN 310	EN 310

The main objective of the research on the milling process using a high-speed steel tool was to determine the effect of the cutting speed on the cutting tool life. To determine the durability of the cutting tool a geometric criterion was used. As a wear factor the maximum wear of the tool flank  $VB_{max}$  is adopted. In addition, it was decided to determine the influence of the basic cutting parameters (cutting speed, feed rate) on the chipboard surface quality and the value of the signals of forces occurring in the machining process, i.e.  $F_x$ ,  $F_y$ ,  $F_z$  (Fig. 1). The milling process experiments were carried out using a high-speed steel double-bit mill of  $\varnothing 14$  mm diameter.



**Figure 1.** Distribution of force components in the milling process (prepared on the basis of Jemielniak (1998))

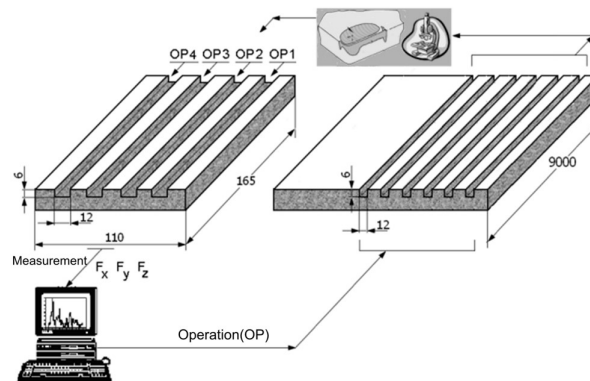
It was assumed that the values of the cutting parameters should correspond to medium quality machining carried out with cutting speeds corresponding to the expected tool life periods. It was also assumed that in the study five durability tests should be performed for five different cutting speeds (Table 2) with constant feed per tooth  $f_z = 0.25$  mm, depth of cut  $a_p = 6$  mm and the width of milling  $a_e = 14$  mm. Each of the durability tests was repeated three times.

**Table 2.** Cutting parameters of the milling process of melamine-faced chipboard

Feed per tooth $f_z$ [mm/tooth]	Cutting speed $v_c$ [m/s]	Rotational speed of the milling cutter $n$ [rev/min]
0.1	13.19	18000
	10.99	15000
	8.79	12000
	6.59	9000
	4.40	6000
0.25	13.19	18000
	10.99	15000
	8.79	12000
	6.59	9000
	4.40	6000
0.4	13.19	18000
	10.99	15000
	8.79	12000
	6.59	9000
	4.40	6000

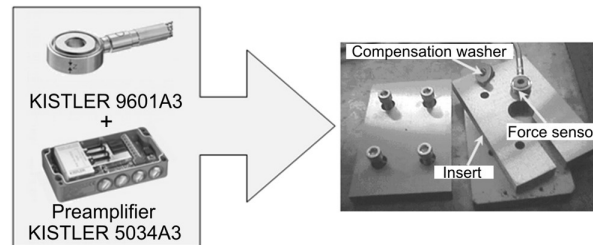
Within each durability test (at a feed of 0.25 mm per tooth) an identical operation was repeated many times, until the tool wear reached the adopted value of the wear criterion. After each operation within a specific durability test the values of the wear factor of the cutting tool were measured using 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, i.e.,  $f_z = 0.1$  mm,  $f_z = 0.25$  mm and  $f_z = 0.4$  mm (Table 2).

Before starting the first milling operation using the new tool, the registration of force signals during one pass (OP1 (Fig. 2)) was done. Then, after the end of each operation consisting of six cuts the tool wear was measured.



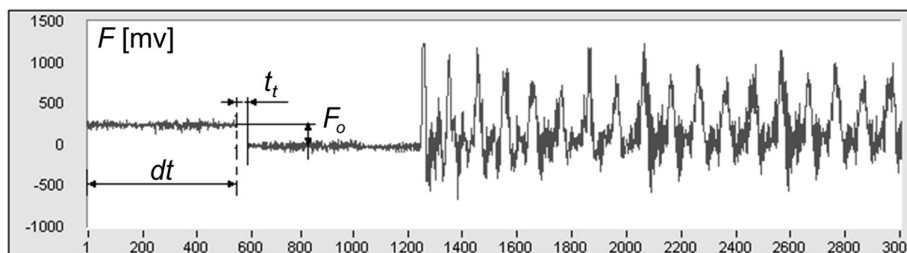
**Figure 2.** Research method

During machining, particularly in the milling process, there is a rapid variation of the values of the cutting forces signals in time. For this reason the measuring system should be characterized by a very low inertia enabling the measurement of rapidly changing values. In the experiments we used a piezoelectric sensor of cutting forces KISTLER type 9601A3 and a 5034A3 charge sensitive preamplifier. The sensor was placed on a special platform (Fig. 3), providing the most accurate measurement of the cutting forces (Jemielniak 2002). The signals of the cutting forces via a charge preamplifier were transferred to the analog-to-digital NI PCI-6034 converter installed in a personal computer and recorded with a sampling rate of 50 kHz.



**Figure 3.** Multicomponent force plate with a mounted sensor of cutting forces

For analysis of the research results we prepared our own computer program in LabView programming language, which allowed us to evaluate the measured values of the recorded signals strength at selected periods of time. The signals recorded by the sensor can be significantly disturbed by external sources, such as friction forces occurring on the guides and acting on the machine head. Some disturbances can be eliminated or reduced by the use of signal taring (Jemielniak 2002). As the reference value, we adopted the signal received after the time  $dt$  from the start of the feed. Taring takes a short moment  $t_t$ . Throughout the taring process, each new signal value, higher than previously recorded, is treated as a new reference value (Fig. 4). Then, the evaluation of the value of the signal measurement begins just after exceeding the adopted value of the signal indicative of the beginning of the cut (Fig. 4) by the force  $F_o$  signal. Therein, we take into account the average value of the measurement from the cut at 0.1 second after the signal value exceeds the initial value  $F_o$ . 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  $F_y$  (Fig. 1).



**Figure 4.** Signal taring

As a wear criterion, the maximum wear of the tool flank  $VB_{max}$  is adopted. According to ISO 8688-1:1996 as the limit value for this wear factor in the case of high-speed steel tools, the value  $VB_{max} = 1$  mm is adopted. Measurement of the value of this factor was performed using a laboratory microscope Mitutoyo TM. In the next stage of the analysis of the results, in order to determine the effect of wear of the blade, feed and cutting speed on the surface texture, it was decided to analyze the quality of the machined surface of the chipboard. 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 uploaded to a computer, and then subjected to digital treatment with the Vision Assistant application in the LabView environment.

In order to determine the quality of the machined surface, we decided to determine the delamination factor  $A_{del}$  measured on the length  $L_p$  of a test piece equal to 165 mm, according to the formula:

$$A_{del} = \frac{S_l}{L_p} \quad (1)$$

where:  $S_l$  – area of delamination,  $L_p$  – measured length of the test piece.

Based on the considerations of Jemielniak (1998; 2002), who described in detail the analytical method for determining the models of economical and efficient machining, the tool life that assures the maximum machining efficiency during the milling process can be defined as:

$$T_q = (-k - 1)t_z \quad (2)$$

and the cutting speed at which the machining efficiency is maximal is equal to:

$$v_q = C_v T_q^{1/k} \quad (3)$$

where:

$t_z$  – the time of tool removal,

$k$  – inclination angle of the line representing the relationship between the tool life and cutting time  $T(v_c)$  plotted on the double logarithmic chart (Taylor's plot),

$C_v$  – cutting speed corresponding to the tool life  $T = 1$ .

Economical tool life depends also on the cost of the machine, maintenance and overheads per hour  $K_O$ , and the cost of the tool per tooth  $K_N$ :

$$T_e = (-k - 1) \left( t_z + \frac{K_N}{K_O} \right) \quad (4)$$

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

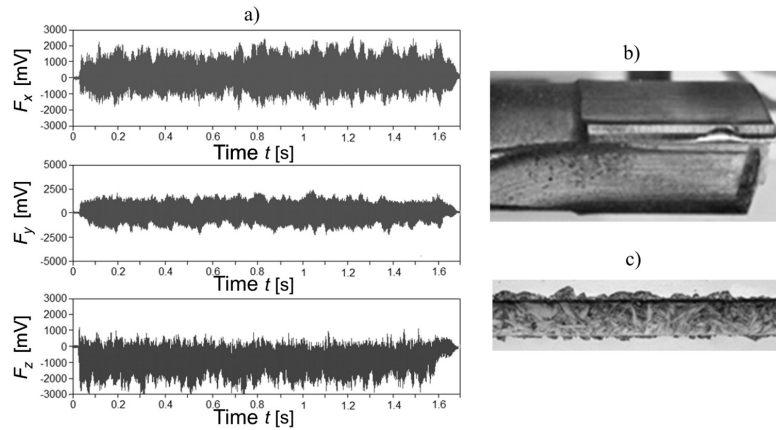
$$v_e = C_v T_e^{1/k} \quad (5)$$

A statistical analysis of the results using multivariate analysis of variance was performed using the *STATISTICA* program. Multivariate analysis of variance allows us to check the significance of the impact of a few independent variables on the dependent variable. Furthermore, multivariate analysis 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 is determined.

## RESULTS

Selected waveforms of cutting force components  $F_x$ ,  $F_y$ ,  $F_z$  with the corresponding state of wear of the cutting tool and quality of the surface finish are shown in Fig. 5. The comparison was made for the three stages of the tool wear, starting with a new tool, through the tool with wear of the tool flank  $VB_{max} = 0.5$  mm and ending with the tool with wear of the tool flank  $VB_{max} = 1$  mm (Fig. 5). The quality of the edge of the melamine-faced chipboard deteriorates with increase of the tool wear, which is expected, as reported by other authors (e.g., Capello 2004; Jemielniak 2002; Laszewicz et al. 2013; Nemili et al. 2007; Tsao and

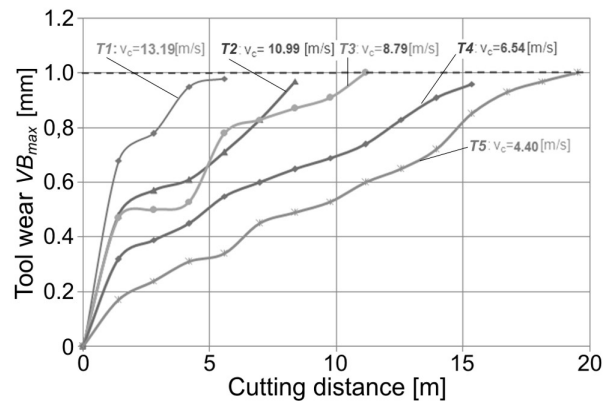
Hocheng 2007). Furthermore, the increase in the value of signals of the cutting force is not proportional to the tool wear. The largest increase in signal amplitude related to the increase of tool flank wear was observed for the force component  $F_y$ .



**Figure 5.** Variation of forces signals  $F_x$ ,  $F_y$ ,  $F_z$  (a) with the corresponding state of cutting tool wear (b) and a view of the chipboard edge (c).

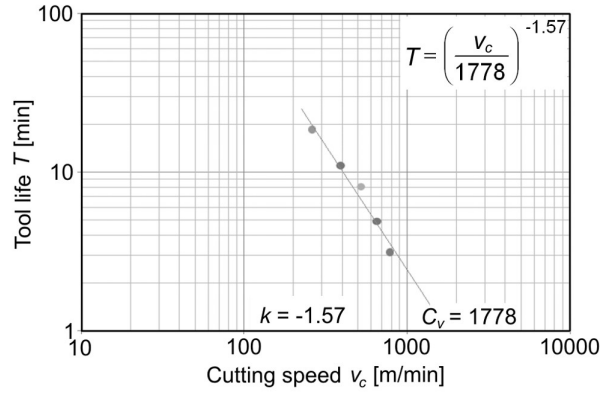
Machining conditions:  $n = 12000 \text{ rev}\cdot\text{min}^{-1}$ ,  $f_z = 0.25 \text{ mm/tooth}$ ,  $VB_{max} = 1 \text{ mm}$

Figure 6 shows the variation of wear of the tool flank  $VB_{max}$  as a function of cutting distance  $l_s$  for five tests carried out with different cutting speeds (see Table 2). There is 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. For example, the milling cutter machining at  $v_c = 13.9 \text{ m}\cdot\text{s}^{-1}$  after a cutting distance of about 6 meters reached the assumed value of tool flank wear  $VB_{max} = 1 \text{ mm}$ , and the allowable tool wear of the milling cutter operated at high cutting speed  $v_c = 4.4 \text{ m}\cdot\text{s}^{-1}$  was reached after about 20 meters. Moreover, in the initial period of tool operation ( $l_s = 0 \div 2 \text{ m}$ ) with increasing cutting speeds a fast increase in tool wear is observed.



**Figure 6.** Variation of tool wear as a function of cutting distance (for five tools),  $f_z = 0.25 \text{ mm/tooth}$

On the basis of durability tests of the milling cutter blade, it was decided to launch a study whose objective was to determine the economical and efficient cutting speeds  $v_e$  and  $v_q$ , respectively. Fig. 7 shows in a double logarithmic coordinate system the effect of the cutting speed on the tool life for the five durability tests carried out with different cutting speeds (see Table 2). Based on the approximation line, the values of the parameters in the Taylor's equation which are necessary to evaluate the values of cutting speeds  $v_e$  and  $v_q$  were determined.



**Figure 7.** Influence of cutting speed on the tool blade life.

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 4), we have to assume the values of constants in Eqs. 3 and 5:  $t_z$ ,  $K_O$ ,  $K_N$ . The values of the parameters were assumed as follows:  $t_z = 2$  min,  $K_O = 35$  EUR/hour,  $K_N = 12$  EUR. The economical value of the 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  $T_q$  was more than ten times smaller than the economical cutting edge life  $T_e$ .

**Table 3** Parameters of efficient and economical wood machining

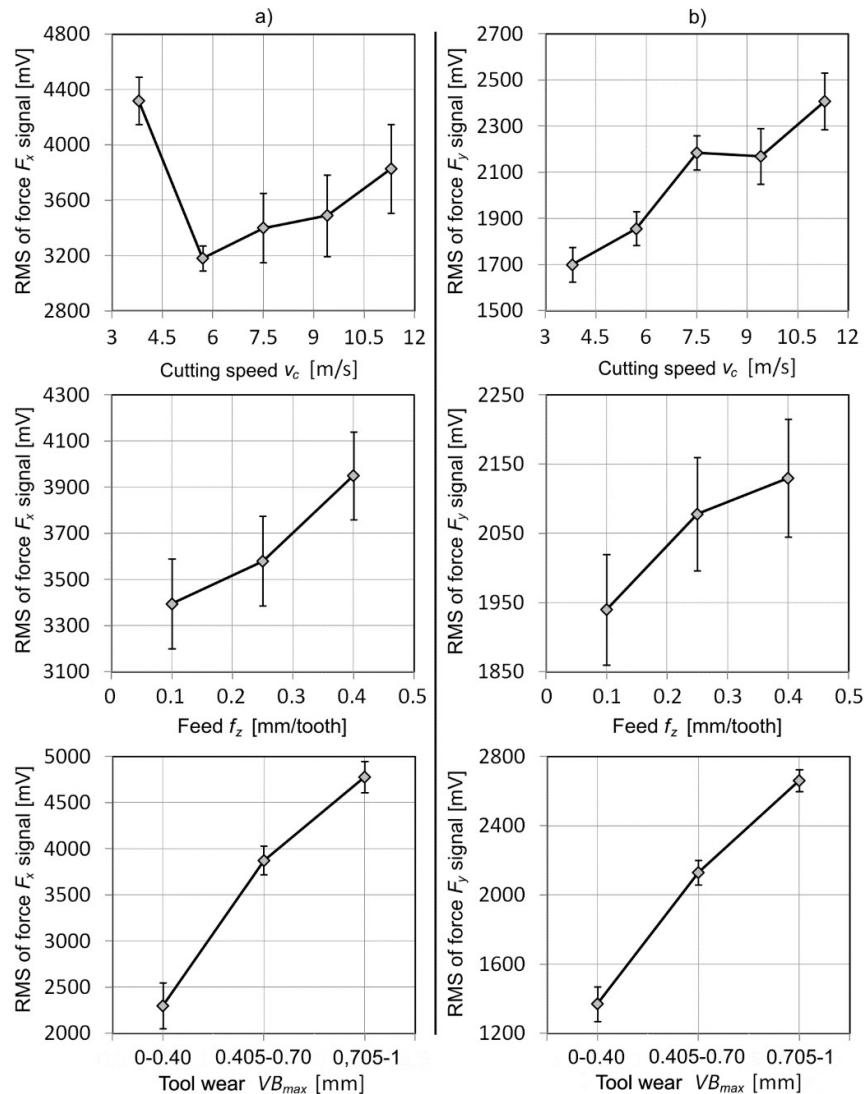
Woodworking model	Cutting speed $v_c$ (m/s)	Rotational speed of milling cutter, $n$ (rev/min)	Tool life $T_q, T_e$ (min)
efficient		>18000	$T_q = 1.14$
economic	5.92	11309	$T_e = 12.54$

For the presented results of the experimental studies three-factor ANOVA analysis was carried out. The significance of the influence of the three controlled parameters  $VB_{max}$ ,  $f_z$  and  $v_c$  on the change of force parameters of the chipboard milling process was 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 tool wear:  $VB_1 = 0-0.04$  mm,  $VB_2 = 0.405-0.7$  mm and  $VB_3 = 0.705-1$  mm. The results of analysis (Table 4) allow us to reject, at the significance level  $p = 0.000$ , the hypothesis about the lack of the effect of parameters  $VB_{max}$ ,  $v_c$  and  $f_z$  on the value of the signal of force  $F_x$ . Statistically significant interactions between the analyzed factors are observed to occur. This is the interaction between the values of forces signals and the products of factors  $VB_{max}$  and  $f_z$  (at  $p = 0.005$ ), and  $VB_{max}$  and  $v_c$  (at  $p = 0.000$ ).

There is 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  $f_z v_c$ , and  $VB_{max}$  and  $v_c$  contribute 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 results in an increase of the root-mean-square values of the  $F_x$  and  $F_y$  signals (Fig. 8).

**Table 4.** Significance of the influence of cutting parameters and tool wear on the value of signals of force components  $F_x$  and  $F_y$

Variables	Significance level $p$	
	$F_x$	$F_y$
$f_z$	0.000	0.004
$VB_{max}$	0.000	0.000
$v_c$	0.000	0.000
$f_z \cdot VB_{max}$	0.005	0.135
$f_z \cdot v_c$	0.656	0.013
$VB_{max} \cdot v_c$	0.000	0.000
$f_z \cdot VB_{max} \cdot v_c$	0.997	0.886



**Figure 8.** Effect of cutting parameters  $v_c$  and  $f_z$ , and tool wear on the value of root-mean-square (RMS) of signals of forces  $F_x$  (a) and  $F_y$  (b)

Determination of the RMS values of the components of the cutting forces is very important in theoretical and practical considerations. When the experimental determination of the components of the cutting forces depends on the technological parameters, the following empirical power relationships are most often used:

$$F_{xRMS} = C_x \cdot VB^{x_x} \cdot f_z^{y_x} \cdot v_c^{z_x} \quad (6)$$

$$F_{yRMS} = C_y \cdot VB^{x_y} \cdot f_z^{y_y} \cdot v_c^{z_y} \quad (7)$$

where:

$C_F, C_M$  – experimentally determined constants depended on cutting conditions,

$x_x, x_y$  – exponents characterising the effect of wear  $VB$  on  $F_{xRMS}$  and  $F_{yRMS}$ ,

$y_x, y_y$  – exponents characterising the effect of feed per tooth  $f_z$  on  $F_{xRMS}$  and  $F_{yRMS}$ ,

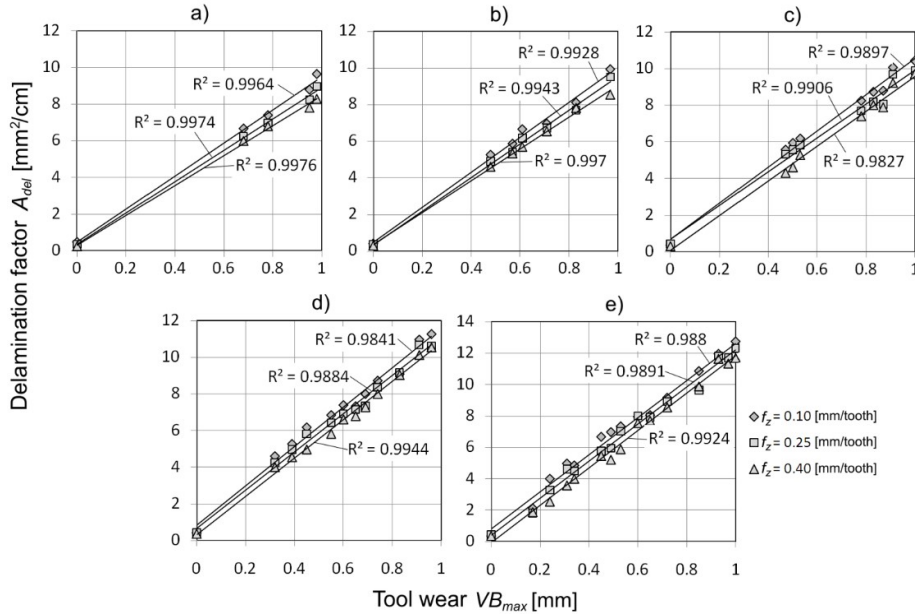
$z_F, z_M$  – exponents characterising the effect of cutting speed  $v_c$  on  $F_{xRMS}$  and  $F_{yRMS}$ .

Based on the experimental results, we evaluated analytically the components of the cutting forces signals on directions  $x$  and  $y$  using multiple regression:

$$F_{xRMS} = 5730 \cdot VB^{0,21} \cdot f_z^{0,11} \cdot v_c^{-0,05} \quad (8)$$

$$F_{yRMS} = 1280 \cdot VB^{0,16} \cdot f_z^{0,11} \cdot v_c^{0,41} \quad (9)$$

Figure 9(a-e) presents the relationship between the delamination factor  $A_{del}$  and the tool wear  $VB_{max}$ . It is observed that there is not only a clear relationship between the tool wear  $VB_{max}$  and the delamination factor  $A_{del}$ , but also a significant effect of the cutting speed on the value of the  $A_{del}$  factor. A reduction in the cutting speed increases the area of delamination, leading to an increase in the value of the  $A_{del}$  factor. In the case of feed per tooth  $f_z$ , we cannot observe its clear effect on intensifying the delamination phenomenon of the chipboard edge. 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.



**Figure 9.** Dependence of the delamination factor  $A_{del}$  vs. tool wear for different cutting speeds:  $v_c = 13.19$  m/s (a),  $v_c = 10.99$  m/s (b),  $v_c = 8.79$  m/s (c),  $v_c = 6.59$  m/s (d) and  $v_c = 4.40$  m/s (e)

Results of the analysis of variance confirmed that the value of the tool wear significantly affects the process of delamination, if we take as a measuring factor the ratio of the surface area of the delamination to the measured length of the test piece (Table 5). Similar conclusions can be drawn in relation to the cutting speed's effect on the value of the factor  $A_{del}$  (at  $p = 0.000$ ). To summarize, both a change in the cutting speed and tool wear have a statistically significant effect on the area of the 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 analyzed parameters on the value of the factor  $A_{del}$ .

**Table 5.** Significance of the influence of cutting parameters and the tool wear on the value of delamination factor  $A_{del}$

Variables	Significance level $p$
$f_z$	0.092
$VB_{max}$	0.000
$v_c$	0.000
$f_z \cdot VB_{max}$	0.972
$f_z \cdot v_c$	0.999
$VB_{max} \cdot v_c$	0.051
$f_z \cdot VB_{max} \cdot v_c$	1.000

Delamination is the main damage observed during the machining of chipboard. This phenomenon is particularly undesirable in the case of melamine-faced chipboards, which are widely used in the furniture industry.

The edge quality of the tested melamine-faced chipboard gets worse with the increase in tool wear, which confirms the findings of other authors. However, an increase in the value of the signals of the cutting force component, which are commonly used to diagnose the wear of the blade, is not proportional to the increase of the wear of  $VB_{max}$ . The largest increase in signal amplitude associated with an increase of tool wear was observed for the component  $F_y$  of cutting force.

There is a clear relationship between the cutting speed and the length of the tool life under the cut. In the initial period of tool operation, in the cutting length range of 0–2 m, with increasing cutting speed a rapid increase in tool wear as a function of cutting length is observed.

The economical cutting speed can be obtained on a standard CNC machine. The cutting speed that ensures the maximum efficiency was much higher than the economical speed and often exceeds the maximum cutting speed that it is possible to obtain on a standard CNC woodworking machine.

The results of three-factorial analysis of variance indicate that there are statistically significant interactions between the value of the force signal and the products of factors  $VB_{max}$  and  $f_z$  (at  $p = 0.005$ ) and  $VB_{max}$  and  $v_c$  (at  $p = 0.000$ ). The increase in the value of feed per tooth and the tool wear causes an increase in the root-mean-square value of force signals  $F_x$  and  $F_y$ .

A decrease in cutting speed and an increase in tool wear  $VB_{max}$  cause an increase of the area of delamination. This leads to an increase in the value of delamination factor  $A_{del}$ . In the case of feed per tooth, there was no clear effect of this parameter on intensifying the phenomenon of delamination. Both the change in the value of the cutting speed and the tool wear have a statistically significant impact on the area of delamination. Furthermore, a change in the feed per tooth has no significant effect ( $p = 0.092$ ) on the  $A_{del}$  factor.

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**Streszczenie:** *Frezowanie płyty wiórowej narzędziem ze stali szybkoobrotowej.* W artykule przedstawiono wyniki badań zużycia freza ze stali szybkoobrotowej podczas frezowania płyty wiórowej laminowanej. Doświadczalne badania wykazały wpływ prędkości skrawania i posuwu na ostrze na wartość sygnałów siły w procesie frezowania, a także na wartość współczynnika rozwarstwiania krawędzi płyt wiórowych. Znaczenie wpływu parametrów procesu cięcia i zużycia narzędzia na wartość współczynnika rozwarstwiania określono przy użyciu analizy wielowymiarowej wariancji. Delaminacja jest główną wadą obserwowaną podczas obróbki płyty wiórowej. Analiza statystyczna wyników eksperymentalnych wskazuje, że głównymi parametrami określającymi stopień uszkodzenia krawędzi płyty wiórowej są zużycie ostrza narzędzia i prędkość skrawania. Przeprowadzono także analizę obróbki w aspekcie ekonomicznym.

Corresponding author:

Joanna Zielińska-Szwajka,  
Stalowa Wola  
37-450 Stalowa Wola, Kwiatkowskiego 4, Poland  
email: j.zielinska@prz.edu.pl