Drewno 2017, Vol. 60, No. 199
DOI: 10.12841/wood.1644-3985.189.09

Krzysztof SZWAJKA, Tomasz TRZEPIECIŃSKI

THE INFLUENCE OF MACHINING PARAMETERS AND TOOL WEAR ON THE DELAMINATION PROCESS DURING MILLING OF MELAMINE-FACED CHIPBOARD

The results of investigations into the wear of a high-speed steel double-bit mill during the milling of melamine-faced chipboard are presented in this paper. The experimental investigations 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 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. In the research, we used an industrial cutting force sensor. The possibility of the application of the industrial sensor to measure the signals of force parameters during milling is investigated. In the case of feed per tooth, there was no clear effect of this parameter on intensification of the delamination phenomenon.

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

Introduction

Wood materials in the form of chipboard, fibreboard and plywood have mainly been used in the furniture and construction industries as insulation materials, windows and doors, floor elements and furniture frontages. An increase in the use of wood-based panels, i.e. MDF (medium density fibreboard), HDF (high density fibre), chipboard and fibreboard has been observed in the construction industry [Thoemen et al. 2010; Vanya 2012]. Among the materials used in the furniture industry, as much as 90% of materials were wood-based panels. Multilayer wood-based materials have been 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], as the adhesive.

The tool wear mechanisms presented in the machining of wood based products may be considered as gross fracture or abrasion, erosion, chipping,

Krzysztof SZWAJKA (*kszwajka@prz.edu.pl*), Faculty of Mechanical Engineering and Technology, Rzeszow, University of Technology, Stalowa Wola, Poland; Tomasz TRZEPIECIŃSKI✉ (*tomtrz@prz.edu.pl*), Department of Materials Forming and Processing, Rzeszow University of Technology, Rzeszów, Poland

chemical and electrochemical corrosion, microfracture, and oxidation [Lino et al. 2009; Sheikh-Ahmad and Bailey 1999]. Gross fracture has resulted in the failure of the tool in the early stages of the cut, while the other mechanisms have acted progressively [Lino et al. 2009]. Atkins [2009] reported that the temperature of the cutting tool and the cutting forces involved were crucial factors governing tool wear mechanisms in wood machining processes, because hardness and toughness degraded with increasing temperature. Sheikh-Ahmad et al. [2003] and Ratnasingam et al. [2010] have shown that the temperature and cutting forces at the tool edge were dependent on several machining factors, such as cutting speed, depth of cut, feed speed.

The progressive loss of the cutting ability of tools due to their wear negatively affected the quality and accuracy of the machined surface. A general review of the prediction of surface roughness in machining was carried out by Benardos and Vosniakos [2003]. The degree of damage (delamination) depended on the method and type of machining, cutting parameters, and bonds, but predominantly on the condition of the cutting tool [Knorz et al. 2014, Porankiewicz et al. 2005].

The mechanical properties of chipboard affected the consumption of carbide cemented tools and the value of the force parameters during the milling process. Increasing the thrust force and cutting speed by changing the cutting parameters also accelerated the wear of the tool during the machining of wood-based materials [Valarmathi et al. 2013]. Cutting forces can be seen as a control parameter for many phenomena involved in the milling of laminated materials.

The most important criterion for assessing the quality of processing of wood--based materials was the state of the edge of the chipboard [Palanikumar et al. 2009]. The quality was assessed, firstly , on the basis of the damage to the laminate in the vicinity of the processing zone, and then on the bead of the particleboard edge. Even one clearly visible chip in the laminate on the edge of the board led to the board's rejection from further production processes, and simultaneously raised the total cost of production. Delamination was the main damage observed during machining of chipboard and was intensified with increasing tool wear [Tsao and Hocheng 2007].

To determine the area of the damage (delamination) to the edge of the chipboard, commonly used indicators of delamination took into account the number of detachments, the width of the delamination, the diameter of the delamination (during drilling), or the surface area of the delamination [Romoli and Dini 2008; Tsao et al. 2012].

Aguilera et al [2000] and Costes et al. [2003] investigated the influence of density changes on cutting force components in machining medium density fibreboards. The findings led to the conclusion that there was a close relationship between cutting parameters and surface roughness, this being greatly influenced by changes in specific gravity within the profile of the panel.

Many investigations were carried out to analyse the machining characteristics of MDFs [Dippon et al. 2000; Engin et al. 2000, Kowaluk et al. 2007], which were focused mainly on the quality of the surface finish and the forces during cutting. Dawim et al. [2008] found that spindle speed played a significant role on the surface roughness as a function of the material removal rate. The results of the works of Aslan et al. [2008] and Sulaiman et al. [2009] indicated that cutting conditions, the material properties of the work piece and tool, as well as cutting parameters (i.e. cutting depth, cutting speed, feed rate) significantly influenced the surface quality of machined MDF.

The machining of wood-based materials has not received much attention in literature [e.g. Lin et al. 2006; Pałubicki 2006; Szwajka and Górski 2006], while the process of drilling and milling of metals has been intensively studied [e.g. Dawim 2008; Grzesik 2016]. One of the major issues in machining, not only of wood-based materials, was the selection of suitable cutting parameters. Pałubicki [2006] explored the problems of laminated particleboard machining, including an analysis of edge defects. The influence of the tool's bluntness and particleboard's production parameters on fracture and chip deformation were studied by i.e. Beer et al. [2005] and Kowaluk et al. [2004]. Nevertheless, as Kowaluk et al. [2006] stated that there was still no information about the work of cutting distribution (on the work of new surface creation and work of chip deformation) in particleboard milling with variable cutting speeds.

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.

Material and methods

A typical industrial and melamine-faced 18 mm thick chipboard was used in the experiments. The U511SM chipboard was manufactured by Kronopol. There was a clear differentiation in the density of the material across the thickness of the melamine-faced chipboard as a result of its multilayer structure. The values of the selected physical-mechanical properties of the chipboard were as follows: moisture content 6.0%, density 658.46 kg/m^3, bending strength 16.39 N/mm^2, bending elasticity modulus 2453 N/mm^2, transverse tensile strength 0.43 N/mm^2.

The measurement of the density profile through the chipboard thickness (fig. 1) was carried out using a GreCon DA-X instrument. The density in the middle part of the thickness was about 85% of the density near to the outer surface layer.

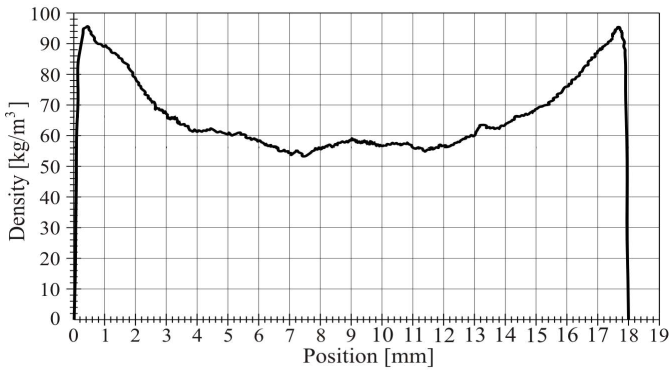

Fig. 1. Density profile through the thickness of the chipboard measured using a GreCon DA-X instrument

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} was adopted. 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 the forces occurring in the machining process, i.e. F_x, F_y, F_z (fig. 2).

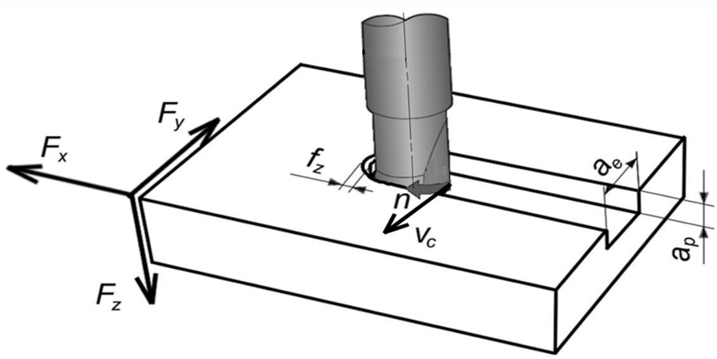

Fig. 2. Distribution of force components F_x, F_y, and F_z in the milling process: a_e – width of milling, a_p – depth of cut, f_z – feed per tooth, *n* - rotational speed of the milling cutter, v_c – cutting speed (prepared on the basis of Jemielniak [1998])

The milling process experiments were carried out using a HS18-0-1 high-speed steel double-bit mill of ∅ 14 mm diameter and the following geometry: a rake angle of 15° and a clearance angle of 26°. The experiments were carried out on a Busellato Jet 100 milling machine with a spindle power of 7.5 kW, a maximum spindle speed of 18000 RPM, and a maximum feed rate of 50 m/min. The measurements were carried out at ambient temperature.

It was assumed that the values of the cutting parameters would correspond to typical parameters of machining used in industrial conditions. The values of the machining parameters were as follows:

- feed per tooth f_z: 0.1, 0.25 and 0.4 mm, which, according to the formula $f_n = 2f_z$ corresponds to feed per revolution f_n: 0.2, 0.5, and 0.8 mm, respectively.
- cutting speed v_c: 4.40, 6.59, 8.79, 10.99 and 13.19 m/s,
- rotational speed of the milling cutter n: 6000, 9000, 12000, 15000 and 18000 rev./min, which corresponded to the feed speed f (tab. 1).

It was also assumed that five tool blade durability tests would be performed in the study for five different cutting speeds with constant feed per revolution $f_n = 0.5$ 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 1. Cutting speed used in investigations

Rotational speed of the milling cuter n [rev./min]	Feed per revolution f_n [mm]	Feed speed f [m/min]
6000	0.2	1.2
	0.5	3.0
	0.8	4.8
9000	0.2	1.8
	0.5	4.5
	0.8	7.2
12000	0.2	2.4
	0.5	6.0
	0.8	9.6
15000	0.2	3.0
	0.5	7.5
	0.8	12.0
18000	0.2	3.6
	0.5	9.0
	0.8	14.4

Within each durability test (at $f_n = 0.2$ mm, $f_n = 0.5$ mm and $f_n = 0.8$ mm.) an identical operation was repeated, until the tool wear reached the adopted value of the wear criterion $Vb_{\max} = 1$ mm. 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.

The significance of the effect of cutting process parameters and tool wear on the delamination process was determined using a multivariate analysis of variance.

Before starting the first milling operation using a new tool at f_n = 0.2 mm, the registration of force signals was carried out during one cut (OP1 (fig. 3)). Then, the cutting force components were measured during six cuts (C1-C6 in fig. 3). After the end of each operation consisting of six cuts tool wear was measured. The investigations of tool wear (after one cut) and cutting force components (CFC) during six cuts were carried out on one workpiece. After the registration of cutting forces the tool was dismounted from the spindle and wear was measured. Next, the measurements of cutting forces and tool wear were repeated at f_n = 0.5 mm and f_n = 0.8 mm on a new workpiece, starting with a new tool. An algorithm for experimental procedure is shown in figure 4.

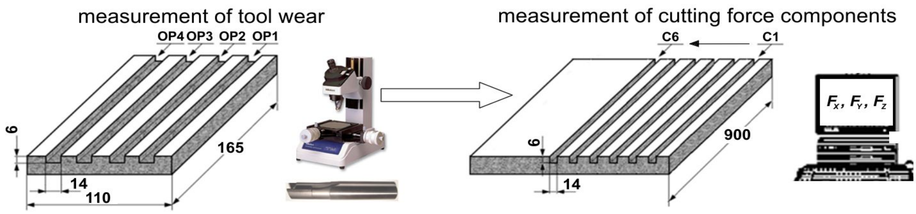

Fig. 3. The research method consisted of milling parallel grooves and registration of the cutting forces; tool wear was measured after the end of each operation consisting of six cuts

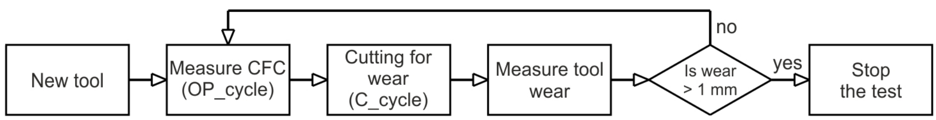

Fig. 4. An algorithm for experimental procedure

During machining, particularly in the milling process, there was a rapid variation of the values of the cutting force 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 an industrial piezoelectric sensor of cutting forces KISTLER type 9601A3 and a 5034A3 charge sensitive preamplifier. The sensor was placed on a multicomponent force plate, thus providing the most accurate measurement of the cutting forces. The signals of the cutting forces were transferred via a charge preamplifier to the analog-to-digital NI PCI-6034 converter, installed in a personal computer and recorded with a sampling rate of 50 kHz.

For an analysis of the research results we prepared our own computer program in LabView 7.1 software, which allowed us to evaluate the measured values of the recorded signal 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 1998]. The method of signal taring of force signals is presented in figure 5. An analysis of the values of the signals started when the feed was turned on by the machine's control system.

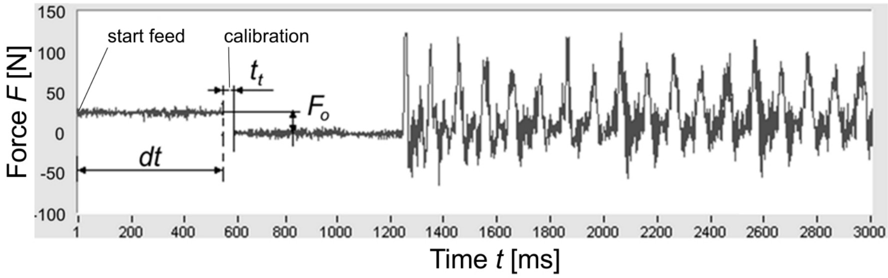

Fig. 5. Scheme of signal taring for reducing the disturbances in signals recorded by the industrial piezoelectric sensor

After buck-off at time *dt*, the average force F_0 acting on a sensor at time t_t was determined. The average force evaluated was taken as a reference value ($F = 0$). The duration of *dt* should be long enough to stabilise forces during tool input. However, the sum of time *dt* and t_t must be shorter than the time of tool input. The cutting force value was evaluated as the difference between the measured force value and F_0 force value.

The maximum wear of the tool flank $VB_{\max}$ was adopted as a criterion of wear. According to ISO 8688-1:1996 [ISO 1996] the limit value for this wear factor in the case of high-speed steel tools had the value $Vb_{\max} = 1$ mm. In the next stage of the results analysis , in order to determine the effect of wear of the blade, feed and cutting speed on the surface texture, it was decided to analyse the quality of the edge of the chipboard. Based on the digital images of the machined surface obtained during the process of the registration 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 post--processing to determine the area of delamination with the Vision Assistant application in the LabView environment (fig. 6).

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 $A_{del} = S_l/L_p$, where: S_l – area of delamination, L_p – measured length of the test piece.

Many authors [e.g. Gaitonde et al. 2008b; Tsao and Hocheng 2007] used analysis of variance to identify the level of importance of the machining parameters for the delamination factor. In most cases, the analysis of variance used $p = 0.05$ to test for significant differences between factors and levels [Gaitonde et al. 2008b; Valarmathi et al. 2013]. A statistical analysis of the results using multivariate analysis of variance was performed using the Statistica program. The statistical significance of cutting parameters was determined taking into account the level of significance adopted, $p = 0.05$.

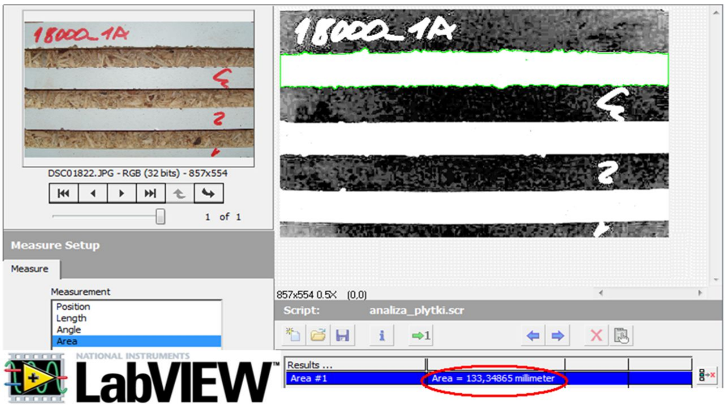

Fig. 6. View of the LabView environment for image analysis of delamination

Results and discussion

With increasing wear of the tool flank $VB_{\max}$, cutting speed v_c had a dominant effect on the delamination factor. Increasing tool wear caused an increase in the area of delamination (fig. 7).

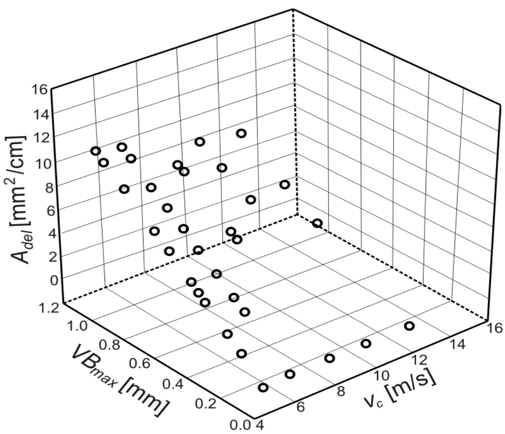

Fig. 7. Effect of $VB_{\max}$ and v_c on the value of area of delamination A_{del}

The quality of the edge of the melamine-faced chipboard deteriorated with an increase in tool wear, which was expected and reported by other authors [e.g.

Tsao and Hocheng 2007]. Furthermore, the increase in the value of signals of the cutting force was not proportional to tool wear.

Figure 8 shows the variation of wear of the tool flank VB_{max} as a function of length of cut l_s for five tests carried out with different cutting speeds (see table 2). There was a clear impact of cutting speed on the length of tool life and this relation was manifested as a decrease in tool life with increasing cutting speed. For example, the milling cutter machining at v_c = 13.9 m/s after a cutting distance of about 6 metres reached an assumed value of tool flank wear Vb_{max} = 1 mm, and the allowable tool wear of the milling cutter operated at low cutting speed v_c = 4.4 m/s was reached after about 20 meters. Moreover, a rapid increase in tool wear was observed in the initial period of tool operation (l_s = 0-2 m) as cutting speeds increased.

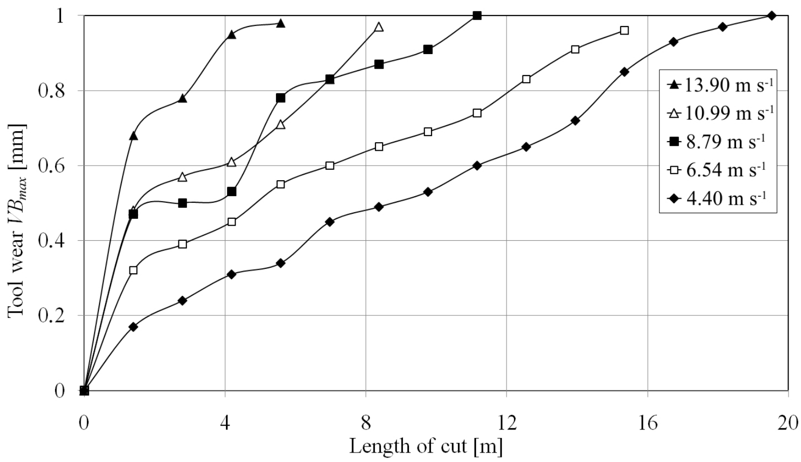

Fig. 8. Variation of tool wear as a function of cutting distance (for five tools), f_n = 0.5 mm

A three-factor variance analysis was carried out on the results of the experimental studies presented. The significance of the influence of the three controlled parameters VB_{max}, f_n and v_c on the change of force parameters of the chipboard milling process was described. The change in tool wear during the operation was a continuous process until the wear of the tool flank reached a critical value. The analysis assumed the following ranges of change in tool wear: VB_1 = 0-0.4 mm, VB_2 = 0.405-0.7 mm and VB_3 = 0.705-1 mm.

The results of the analysis (tab. 2) allowed us to reject, at the significance level of p = 0.000, the hypothesis that the parameters VB_{max}, v_c, and f_n had no effect on the value of force F_x. Statistically significant interactions between the analysed factors were observed to occur. This is the interaction between the values of forces signals and the products of factors $VB_{\max}$ and f_n (at $p = 0.005$), and $VB_{\max}$ and v_c (at $p = 0.000$).

Table 2. Significance of the influence of cutting parameters and the tool wear on the value of force components F_x and F_y, and delamination factor A_{del}

Variables	Significance level p		
	F_x	F_y	A_{del}
f_n	0.000	0.004	0.092
$VB_{\max}$	0.000	0.000	0.000
v_c	0.000	0.000	0.000
$f_n \cdot VB_{\max}$	0.005	0.135	0.972
$f_n \cdot v_c$	0.656	0.013	0.999
$VB_{\max} \cdot v_c$	0.000	0.000	0.051
$f_n \cdot VB_{\max} \cdot v_c$	0.997	0.886	1.000

The two-factor formulas $f_n{\cdot}v_c$, and $VB_{\max}$ and v_c contributed important predictive information to the analysis of variance at a level of significance $p = 0.013$ and $p = 0.000$, respectively. The character of the effect of feed per revolution f_n and wear $VB_{\max}$ on the value of force components F_x and F_y was clear in the range of values of these parameters applied in the study; that is, an increase in the value of these parameters resulted in an increase in the values of force components F_x and F_y (figs. 9-11). As found by Gaitonde et al. [2008b], less cutting force was required to shear the material, resulting in minimal delamination. The basic parameter that helped to effectively diagnose the milling operation was the force normal to the feed direction, which provided a very responsive indicator of the changes in edge geometry.

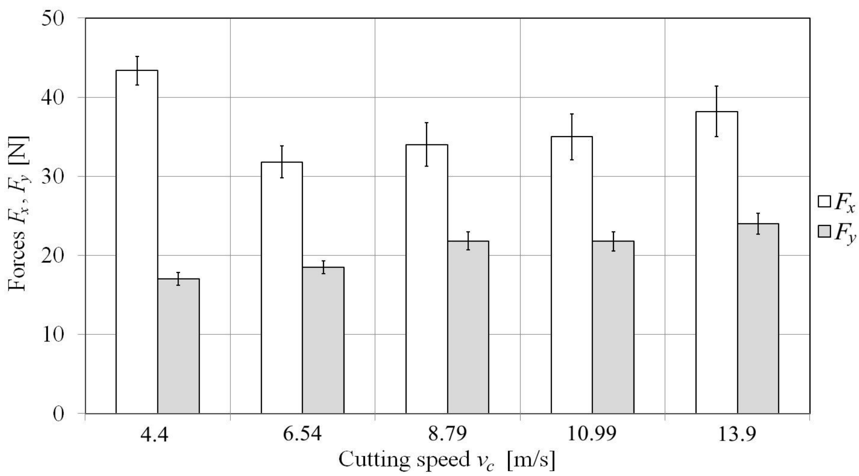

Fig. 9. Effect of cutting speed v_c on the value of forces F_x and F_y

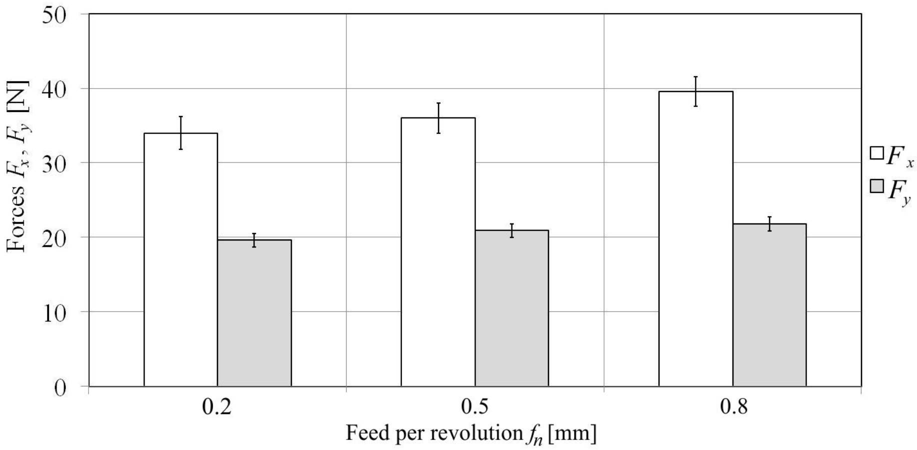

Fig. 10. Effect of feed per revolution f_n on the value of forces F_x and F_y

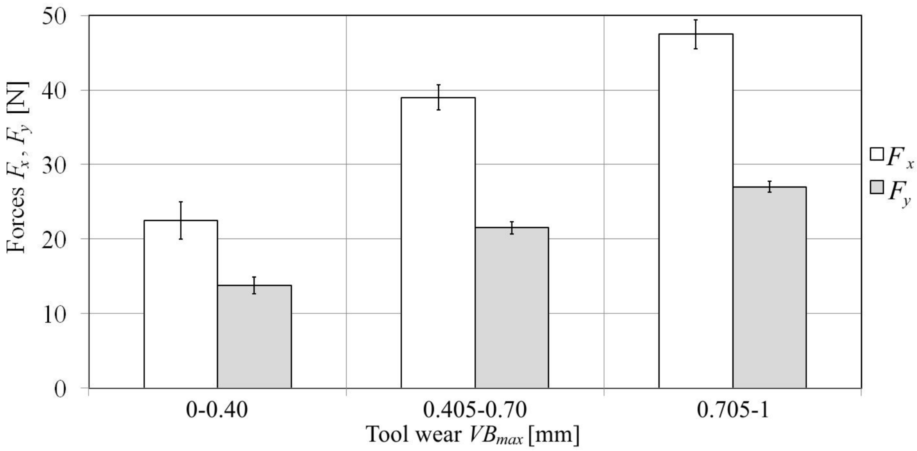

Fig. 11. Effect of wear of the tool flank VB_{max} on the value of forces F_x and F_y

Figure 12(a-e) presents the relationship between the delamination factor A_{del} and tool wear VB_{max}. A reduction in the cutting speed increased the area of delamination, leading to an increase in the value of the A_{del} factor. The same conclusion was drawn by Gaitonde et al. [2008b], who has found that by employing a higher cutting speed it was possible to reduce the tendency to delaminate during drilling.

To summarize, both a change in cutting speed and tool wear had a statistically significant effect on the area of delamination. However, a change in feed per tooth had no significant effect (p = 0.092). There was no statistically significant synergistic effect on the products of the parameters analysed on the value of the factor A_{del}.

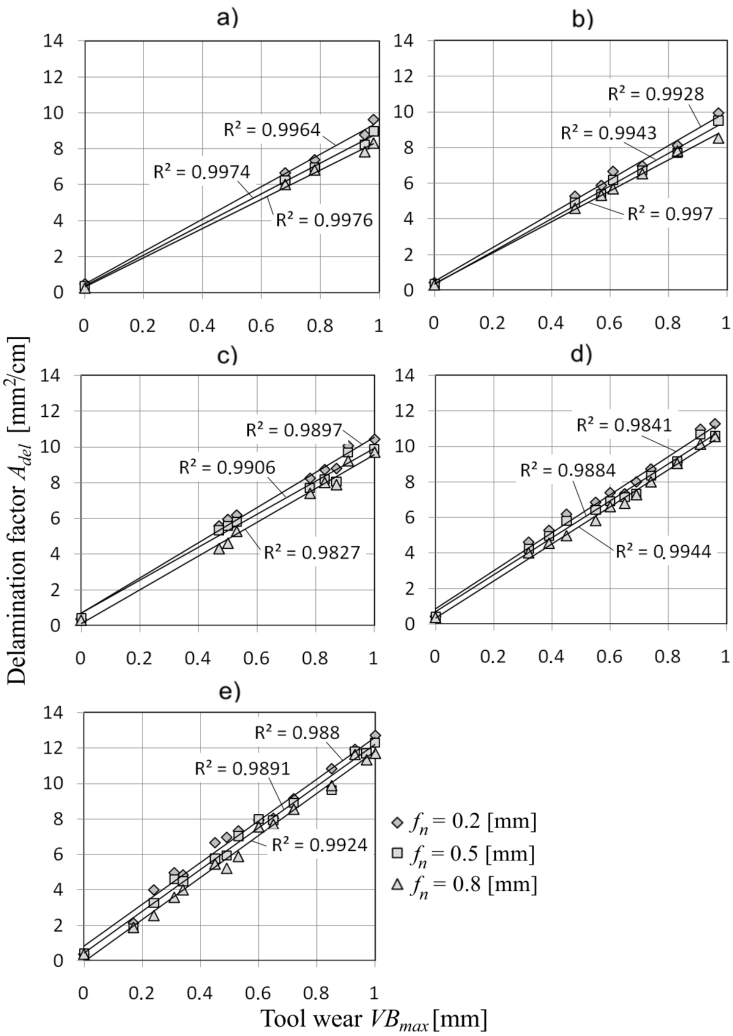

Fig. 12. Dependence of the delamination factor A_{del} vs. tool wear for different cutting speeds: v_c = 13.19 m/s (a), v_c = 10.99 m/s (b), v_c = 8.79 m/s (c), v_c = 6.59 m/s (d) and v_c = 4.40 m/s (e)

The results of the analysis of variance confirmed that the value of tool wear significantly affected the process of delamination, if we took as a measuring factor the ratio of the surface area of the delamination to the measured length of the test piece (tab. 1).

Conclusions

The following conclusions can be drawn with regard to the milling of melamine--faced chipboard:

– An increase in the value of the cutting force component was not proportional to the increase in the wear of VB_{max}. The largest increase in signal amplitude associated with an increase in tool wear was observed for the F_x component of cutting force.
– There was a clear relationship between the cutting speed and the length of 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 was observed as a function of cutting length.
– The results of the three-factoral analysis of variance indicated that there were statistically significant interactions between the value of the forces and the products of factors VB_{max} and f_n, and VB_{max} and v_c.
– A decrease in cutting speed and an increase in tool wear VB_{max} caused an increase in the value of the delamination factor A_{del}.
– In the case of feed per tooth, there was no clear effect of this parameter on the intensification of the delamination phenomenon.

References

Aguilera A., Meausoone P.J., Mertin P. [2000]: Wood material influence in routing operations: the MDF case. Holz als Roh Werkstoff 58: 278-283

Aslan S., Coşkun H., Kiliç M. [2008]: The effect of the cutting direction, number of blades and grain size of the abrasives on surface roughness of Toros cedar woods. Building and Environment 43 [5]: 696-701

Atkins T. [2009]: Toughness and processes of material removal. Wear 267 [11]: 1764-1771

Beer P., Kowaluk G., Sinn G., Dziurka D. [2005]: Mechanical properties of particleboards induce cutting quality. Proceedings of: 17th International Wood Machining Seminar, 26-28 September 2005. Rosenheim: 45-52

Benardos P.G., Vosniakos G.C. [2003]: Predicting surface roughness in machining: a review. International Journal of Machine Tools and Manufacture 43 [8]: 833-844

Costes J.P., Deces-Petit C., Altintas Y., Ko P. [2003]: Estimated stress and friction distributions on tool rake face in the medium density fibreboard cutting process. Forest Product Journal 53: 59-66

Dawim J.P. [2008]: Machining – fundamentals and recent advances. Springer-Verlag, London

Dawim J.P., Clemente V.C., Silva S. [2008]: Surface roughness aspects in milling MDF (medium density fibreboard). International Journal of Advanced Manufacturing Technology 40 [1-2]: 45-55

Dippon J., Ren H., Amara F.B., Altintas Y. [2000]: Orthogonal cutting mechanics of medium density fibreboards. Forest Product Journal 50: 25-30

Engin S., Altintas Y., Amara F.B. [2000]: Mechanics of routing medium density fibreboard. Forest Product Journal 50: 65-69

Gaitonde V.N., Karnik S.R., Davim J.P. [2008a]: Prediction and optimization of surface roughness in milling of medium density fibreboard (MDF) based on Taguchi orthogonal array experiments. Holzforschung 62 [2]: 209-214

Gaitonde V.N., Karnik S.R., Davim J.P. [2008b]: Taguchi multiple-performance characteristics optimization in drilling of medium density fibreboard (MDF) to minimize delamination using utility concept. Journal of Materials Processing Technology 196 [1-3]: 73-78

Grzesik W. [2016]: Advanced machining processes of metallic materials. Theory, modelling, and applications. 2nd Ed., Elsevier, Amsterdam

Jemielniak K. [1998]: Obróbka skrawaniem (Machining). Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa

Knorz M., Schmidt M., Torno S., van de Kuilen J.W. [2014]: Structural bonding of ash (*Fraxinus excelsior* L.): resistance to delamination and performance in shearing tests. European Journal of Wood and Wood Products 72 [3]: 297-309

Kowaluk G., Dziurka D., Beer P., Sinn G., Tschegg S. [2004]: Influence of particleboards production parameters on work of fracture and work of chips formation during cutting [accessed: 12.09.2016]. Electronic Journal of Polish Agricultural Universities 7 [1]. Available from: http://www.ejpau.media.pl/volume7/issue1/wood/art-01.html

Kowaluk G., Szymański W., Beer P. [2007]: Influence of tools stage on particleboards milling. Wood Research 52 [3]: 75-88

Kowaluk G., Szymanski W., Pałubicki B., Beer P. [2006]: Forces and work of cutting versus cutting speed in laminated particleboards milling. Proceedings of: 5th International Science Conference Trieskové a Beztrieskové Obrábanie Dreva, 12-14 October 2006. Starý Smokovec: 173-178

Lin R.J.T., Houts J.V., Bhattacharyya D. [2006]: Machinability investigation of medium density fibre board. Holzforschung 60 [1]: 71-77

Lino F.J., Guimãraes J., Teixeira L., Baptista A.M., Fernandes T., Figueiredo F. [2009]: Comparison of different cemented tungsten carbides applied to particleboard machining end mills. Proceedings of: Euro PM2009 Congress, 12-14 October 2009. Copenhagen: 311

Palanikumar K., Prakash S., Manoharan N. [2009]: Experimental investigation and analysis on delamination in drilling of wood composite medium density fiber boards. Materials and Manufacturing Processes 24 [12]: 1341-1348

Pałubicki B. [2006]: Badania nad jakością obróbki elementów meblowych z płyt wiórowych laminowanych (Research on machining quality of furniture elements made of laminated chipboards). Akademia Rolnicza, Poznań [unpublished]

Porankiewicz B., Sandak J., Tanaka C. [2005]: Factors influencing steel tool wear when milling wood. Wood Science and Technology 39 [3]: 225-234

Ratnasingam J., Ma T.P., Ramasamy G. [2010]: Tool temperature and cutting forces during the machining of particleboard and solid wood. Journal of Applied Sciences 10: 2881-2886

Romoli L., Dini G. [2008]: Experimental study on the influence of drill wear in CFRP drilling process. Proceedings of: 6th CIRP International Conference on Intelligent Computation in Manufacturing Engineering, , 23-25 July 2008. Naples: 145-149

Sari B., Nemli G., Baharoğlu M., Bardak S., Zekoviç E. [2013]: The role of solid content of adhesive and panel density on the dimensional stability and mechanical properties of particleboard. Journal of Composite Materials 47 [10]: 1247-1255

Sheikh-Ahmad J.Y., Bailey J.A. [1999]: High-temperature wear of cemented tungsten carbide tools while machining particleboard and fiberboard. Journal of Wood Science 45[6]: 445-455

Sheikh-Ahmad J.Y., Lewandowski C.M., Stewart J.S. [2003]: Experimental and numerical methods for determining temperature distribution in a wood cutting tool. Experimantal Heat Transfer 16 [4]: 225-271

Sulaiman O., Rashim R., Subari K., Liang C.K. [2009]: Effect of sanding on surface roughness of rubberwood. Journal of Materials Processing Technology 209: 3949-3955

Szwajka K., Górski J. [2006]: Evaluation tool condition of milling wood on the basis of vibration signal. Journal of Physics: Conference Series 48: 1205-1209

Thoemen H., Irle M., Sernek M. [2010]: Wood-based panels. An introduction for specialists. Brunel University Press, Wentorf

Tsao C.C., Hocheng H. [2007]: Effect of tool wear on delamination in drilling composite materials. International Journal of Mechanical Sciences 49 [8] 983-988

Tsao C.C., Kuo K.L., Hsu I.C. [2012]: Evaluation of a novel approach to a delamination factor after drilling composite laminates using a core-saw drill. International Journal of Advanced Manufacturing Technology 59 [5-8]: 617-622

Valarmathi T.N., Palanikumar K., Latha B. [2013]: Measurement and analysis of thrust force in drilling of particle board (PB) composite panels. Measurement 46 [3]: 1220-1230

Vanya C. [2012]: Damage problems in glued laminated timber. Drewno 55 [188]: 115-128

List of standards

ISO 8688-1:1996 Tool life testing in milling – Part 1: Face milling

Acknowledgements

The research leading to these results has received funding from the People Programme (Marie Curie International Research Staff Exchange) of the European Union's FP7/2007-2013/ under REA grant agreement no. PIRSES--GA-2013-610547.

Submission date: 22.10.2016

Online publication date: 19.05.2017