AN EXAMINATION OF THE TOOL LIFE AND SURFACE QUALITY DURING DRILLING MELAMINE FACED CHIPBOARD

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ABSTRACT

An analysis of the cutting process and tool wear during machining from metal materials has been the subject of many studies. On the other hand, the tool life when machining from wood materials has not received much attention. Optimisation of the cutting process consists of the appropriate selection of major processing parameters as the cutting depth, feed rate and cutting speed in order to ensure adequate machining accuracy at minimum cost, and appropriate process efficiency. Here, we present the results of experimental tests of wearing drills with carbide blades during processing of melamine faced chipboard (MFC). To evaluate the surface quality of the chipboard the maximum radius and area of delamination around the chipboard blind hole are adopted. These parameters are determined independently at the hole entry and exit. Statistical analysis of results using multifactor analysis of variance was carried out. The tool life of drills depends on many combinations of cutting parameters and the wear of the drill blade. In the drilling process, the value of the thrust force mainly depended on wear of tool flank and the feed rate. The cutting speed has little effect on the amount of thrust force and cutting torque.

KEYWORDS: Chipboard, delamination, drilling, particleboard, tool life, tool wear.

INTRODUCTION

During drilling operations of melamine-faced chipboard, there is a tendency to delamination of the material under the influence of cutting forces. Delamination is the main damage observed during the drilling of laminated chipboard (Watson et al. 2013). For this reason, the delaminations are a factor that significantly determines the surface quality of the material for structural applications. Davim et al. (2007b) conducted investigations to determine the relationship between cutting parameters and delamination of the chipboard at the hole entry and exit during drilling of medium-density fibreboard (MDF). It was found that there is an im-portant role of the cutting speed on the evolution of the delamination factor as a function of the material removal rate (MRR). Aguilera et al. (2000) found that high density and low chip thickness produce optimal levels of surface roughness in machining of MDF panels.

Concerning the evaluation of delamination around the hole, there are reports (Chen 1997, Davim and Reis 2003a, Feito et al. 2014) where delamination factors have been used based on the measurement of the maximum diameter of observed delamination, or an area of delamina-tion has been defined. Recently, however, certain workers increasingly use the dimensionless factor to evaluate delamination. Chen (1997) proposed a concept of delamination factor Fd to analyse and compare easily the delamination degree in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates.

Benzeggagh and Kenane (1996) proposed that the delamination onset criterion stems from the expression of the critical energy release rate for delamination propagation under mixed-mode loading. Palanikumar et al. (2009) investigated the delamination in drilling of MDF and observed that the delamination can be reduced at low feed rates. Prakash and Palanikumar (2011) found that the increase in drill diameter increases the delamination. A similar depend-ence was confirmed by Valarmathi et al. (2013b). Gaitonde et al. (2008b, 2008c) studied the influence of machining conditions on thrust force and concluded that feed rate followed by spindle speed were the most significant factors in minimising the thrust force value in drilling MDF panels.

To summarise the literature review:
1. Little attention has been paid to the effect of tool wear, feed rates and cutting speeds on the delamination process in wood drilling operations. Most studies are carried out at constant cutting parameters, and thus do not include the interaction effect between the aforementioned factors and the delamination factor.
2. The delamination factor used by Chen (1997) is meaningful only if the delamination has a regular shape. However, very often there are situations when irregular delaminations are formed on the processed material.
3. The factors given by Mehta et al. (1992) and Romoli and Dini (2008), in fact do not re-flect the real damage. These factors define the participation of the damage surface in relation to the nominal surface of the hole.
4. The factor described by Chen (1997) does not include the range of delamination around the hole, only the maximum diameter of the delamination is considered. The factors developed by Mehta et al. (1992) and Romoli and Dini (2008) do not include information about delamination diameters D_{MAX} and D_{NOM}.

These problems in the assessment of tool wear and hole quality in the machining of chipboard motivate our investigations. This study presents the results of experimental research of wear of the cemented carbide drills when processing melamine faced chipboard (MFC). The elements made of MFC are widely used in the furniture industry (Basturk and Guntekin 2009, Güler et al. 2013) where a high quality of the hole edge is required. A statistical analysis of the

results of the experimental tests results was carried out by using multivariate analysis. Drill tool life was determined taking into account many combinations of cutting parameters and tool wear. Furthermore, a new method of determining the economic cutting speed and the cutting speed corresponding to maximum efficiency is proposed.

MATERIAL AND METHODS

Material

In our experiments, a typical industrial and melamine faced 18 mm thick chipboard was used. Melamine faced chipboard is characterised by clear diversity of the material density on the cross section as a result of its multilayer structure. To characterise more accurately the material being processed, the laboratory measurement of the local density, mechanical and physical properties are carried out. The results are shown in Tab. 1.

Tab. 1: Mechanical and physical properties of melamine–faced chipboards used here.

Parameter	Surface soundness ($N \cdot mm^{-2}$)	Transverse tensile strength, ($N \cdot mm^{-2}$)	Bending strength, ($N \cdot mm^{-2}$)	Bending elasticity modulus, ($N \cdot mm^{-2}$)	Density, ($kg \cdot m^{-3}$)
Melamine faced chipboard	1.3	0.43	16.39	2453	670
Standard of testing method	EN 311	EN 319	EN 310	EN 310	EN 323

Methods

Cutting resistance measurement

A Kistler piezoelectronic dynamometer 9601A3 with a Kistler charge amplifier 5073A211 was used to acquire the thrust force and cutting torque.

For the analysis of the acquired data, the computer program (in the LabView programming language) is prepared. It allows, in the selected time range, data handling. The program was based on the automatic determination of values of thrust force and cutting torque in specific time range of the signal. As the signal of thrust force exceeds the threshold adopted at 150 mV, the determination of some selected parameters of both the thrust force Fo and cutting torque M_s, i.e. average value, root mean square is followed. These parameters are evaluated until the signal value of the axial force has fallen below 150 mV. This procedure gives repeatability of signal time range on the basis of which are determined parameter values.

Tool state and machining quality

In investigations of the drilling process, a critical tool wear factor is the adopted wear of the tool flank VB_{max} = 0.2 mm. In addition, it was decided to use another wear factor, i.e. the chord length of corners VBK_E (Fig. 1). The values of the wear factors were measured with a microscope Mitutoyo TM with dropped digital camera eyepiece with a resolution of 600 dpi, which allows image archiving in a personal computer.
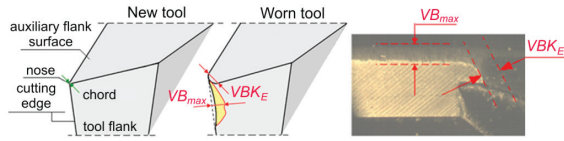
Fig. 1: Adopted wear factors of the cutting tool in the drilling process: VBmax and VBKE.

The quality of drilled surface and damages are associated with machining conditions, cutting parameters, tool geometry, tool and work material, inter alia (Davim et al. 2008, Gaitonde et al. 2008b). Normally, drilling damage like delamination and edge chipping occur in drilling (Valarmathi et al. 2013b).

In order to analyse the quality of the surface of the chipboard, a digital photo of each hole entry and exit is registered. In order to determine the quality of the surface around the hole, we decided to adopt the 2 most commonly used parameters: the maximum radius of delami-nated area R_{max} and the area of delamination A (Fig. 2). Both parameters were determined at the hole entry and exit. In this manner, we determined 4 parameters of the symbols: A_{ent}, A_{exit}, R_{ent}, R_{exit}. To determine the adopted parameters the recorded images were processed in the LabView environment.
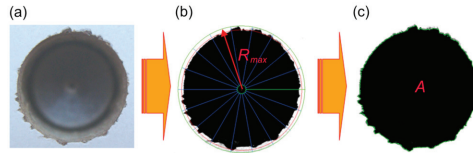

Fig. 2: Digital image processing in LabView environment: a) digital photograph; b, c) images after treatment.

Plan of experiments

The experiments had been carried out using 10 mm diameter cemented carbide drills of grade K20 with 20° helix and 60° point angles. Tests were carried out with the use a standard CNC machining centre Busellato Jet 100. Tab. 2 indicates the factors to be studied and as-signment of corresponding levels. For each, adopted in the investigations feed rates (0.2, 0.25, 0.3) six tests for 5 cutting speeds were carried out. The test was repeated twice at maximum cutting speed. As shown in Tab. 2, the total number of tests is 18. Tests were carried out to the reach maximum accepted value of the blade wear.

Each durability test of the drill consists of repetitive operations, under which the 252 holes are performed. After each completed operation, a measurement of tool wear and evaluation of thrust force, as well as cutting torque, was carried out.

Tab. 2: Assignment of the levels to the factors.

Test no.	Feed rate f_n, (mm/rev)	Cutting speed (m·min⁻¹)	Rotational speed (rpm)
1, 2		376.8	12000
3		314.0	10000
4	0.2	251.2	8000
5		188.4	6000
6		125.6	4000

7, 8		376.8	12000
9		314.0	10000
10	0.25	251.2	8000
11		188.4	6000
12		125.6	4000
13, 14		376.8	12000
15		314.0	10000
16	0.3	251.2	8000
17		188.4	6000
18		125.6	4000

Statistical analysis

Statistical analysis of the results using the multivariate analysis of variance was performed using the *STATISTICA* program. The multivariate analysis of variance allows to check the significance of the impact of a few independent variables on the dependent variable. Furthermore, the multivariate analysis makes it possible take into account in the statistical model the synergistic effect of the product of many variables. 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 AND DISCUSSION

Tool wear and delamination area

The comparison was made for the different stages of tool wear, ranging from a new, where VB_{max} = 0 mm (Fig. 3a) and ending with a blunt blade of VB_{max} = 0.2 mm (Fig. 3b). The increase in the wear results in approximately two-fold increase cutting torque and almost three-fold increase in the maximum thrust force. The new bit exhibits lower thrust and torque over the whole range of the parametric operating conditions (Zhao and Ehmann 2002). However, Feito et al. (2014) found that the new tool showed negligible influence on thrust force.

The increasing of wear parameter VB_{max} value causes increasing the delamination area at the damaged zone (Fig. 4). Hovewer, the delamination at the hole exit was higher than at the hole entry. Similar results were also reported by Feito et al. (2014) and Hocheng and Tsao (2006). Gaitonde et al. (2008a) found that the delamination is linearly related to feed rate and they observed that high-speed cutting plays a major role in reducing damage at the entrance of the hole. According the results of Gaitonde et al. (2008c) the delamination of the hole in MDF panels is caused due to uncut material by the twist drills, which reduces the strength against fatigue.
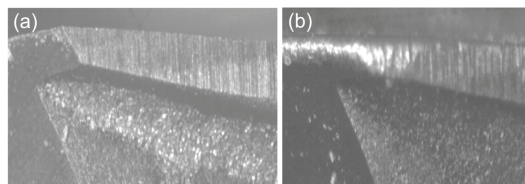

Fig. 3: View of cutting edge of new tool (a) and worn cutting edge of VB_{max} = 0.2 mm.
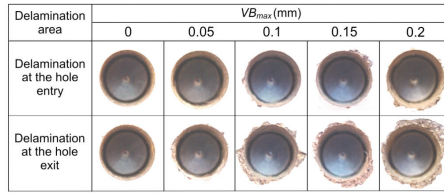
Fig. 4: The view of the delamination zone at the hole entry and exit at n = 10000 rev/min and, f_n = 0.2 mm.

Number of holes

The variations of the value of tool wear VB_{max} as a function of the number of drilled holes for the 3 feed rates and 5 cutting speeds are presented in Fig. 5a-c. Increasing the feed of 0.2 mm/rev to 0.35 mm/rev at a constant minimum cutting speed of n = 4000 rev/min causes that the number of holes drilled through the tool until the critical wear is achieved is reduced by approximately 19 %. With the same increase of feed rate, but at the highest cutting speed n = 12000 rev/min the number of holes is reduced by approximately 31 %. For all of the feed rates in the range of drilled holes 0–800 the wear value is similar for all used speeds are simi-lar. The higher wear value, the difference in the number of holes made at different speeds is more evident. It is well known that the combination of low-feed rate with the high cutting speed is necessary to minimize delamination in drilling of MDF (Gaitonde et al. 2008b). On the other hand the low values of feed rate always ensure minimum thrust force in order to reduce the delamination (Gaitonde et al. 2008c). The investigations made by Davim et al. (2003, 2008) revealed that by employing the higher cutting speeds it is possible to reduce the delamination tendency in drilling. Our results confirmed the conclusion indicated by Davim et al. (2007a). They investigated the defects observed at the entrance and exit sides of drilled MDF panels and established a relationship between the damage features and machining pa-rameters. They have found that the higher cutting speeds should be used to obtain minimal delamination. A reduction in the cutting speed increases the area of delamination. It was especially visible for larger values of tool wear. These findings agree with the results of Mercy et al. (2014).
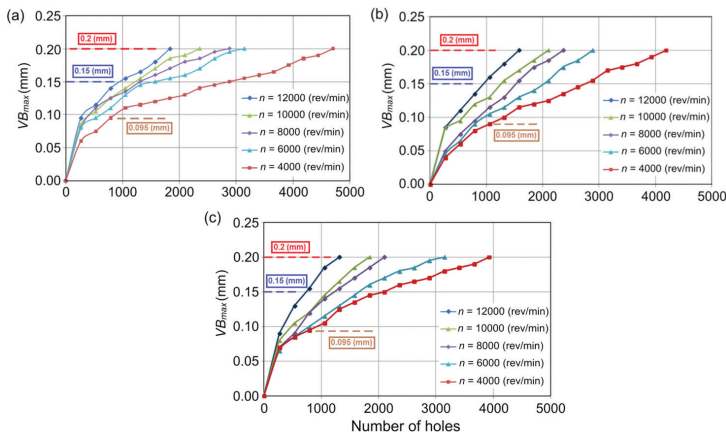

Fig. 5: Variation of tool wear VB_{max} as a function of the number of drilled holes for the five cutting speeds and the feed rates: (a) fn = 0.2 mm/rev, (b) f_n = 0.25 mm/rev and (c) f_n = 0.3 mm/rev.

Wear factors

The factors VB_{max} and VBKE are highly correlated (R2 = 0.97), so in further analyses only the indicator VB_{max} will be used.

To assess the impact of changes in the value of drilling process parameters and parameters of drill wear on the chipboard surface quality, their correlation was examined for 5 durability tests T1-T5 realised with the different adopted cutting speeds. The highest value of the coefficient of determination R^2 is obtained for the dependence of VB_{max} value and the maximum radius of delaminated area at the hole exit R_{exit} (Fig. 6a) and the area of the delamination at the hole exit A_{exit} (Fig. 6b). It is a mathematical confirmation of conclusions drawn based on the visual analysis of the digital photographs of delamination zones of the holes (Fig. 4).

Machining at a high speed was expected to increase the rate of tool wear, which would subsequently deteriorate the surface finish of MDF panels (Lin et al. 2006). However, panels with lower density have rougher surface finishes in comparison to high density panels (Lin et al. 2006).
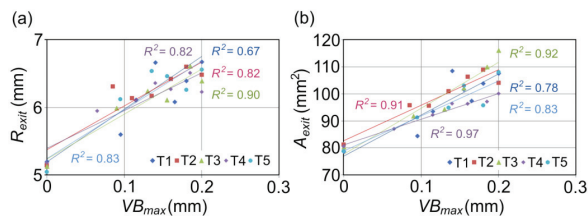

Fig. 6: The effect of wear on the value of the maximum radius of delaminated area Rexit (a) and the area of delamination Aexit (b) at the hole exit.

ANOVA analysis

The effects of cutting speed, feed rate and consumption VB_{max} the value of the geometrical parameters of delamination are evaluated using analysis of variance (ANOVA). It was reported that an ANOVA method is suitable to determine the contribution of process parameters to the measured feature of a product (Gaitonde et al. 2008a, 2008c, Valarmathi et al. 2013a, 2013b, Zhao and Ehmann 2002). The ANOVA technique is a systematic algebraic procedure of decomposing the overall variation in the response observed in an experiment into different components. Each component is attributed to an identifiable cause or the source of variation. The following geometrical parameters were considered:

- the area of the delamination at the hole entry A_{ent},
- the area of the delamination at the hole exit A_{exit},
- the maximum radius of delaminated area at the hole entry R_{ent},
- the maximum radius of delaminated area at the hole exit R_{exit}.

The results of analysis (Fig. 7a) allow one to reject, at the significance level p = 0.000, the hypothesis about the lack of effect of factor VB_{max} on the area of the delamination A_{exit}. So we can say that the value of the tool wear significantly affects the process of delamination, using for assessment the area of the delamination A_{exit}. Similar conclusions can be drawn with re-spect to the impact of cutting speed.

It is observed, at the significance level p = 0.035, the effect of cutting speed on the area of the delamination at hole entry A_{exit}. The impact of the feed rate is statistically insignificant (p = 0.375). In summary, both a change in the cutting speed and wear significantly affects the area of the delamination A_{exit}, while a change in the feed rate has no significant effect on A_{exit}. Furthermore, the interaction of VB_{max} and vc parameters is highly significant (p = 0.026). Davim et al. (2007b) also confirmed the important role of the cutting speed in the evolution of the

delamination factor. Prakash and Palanikumar (2011) used spindle speed, feed rate and drill diameter as the drilling parameters. Their study revealed that the most significant param-eter for delamination is feed rate. The ANOVA analysis conducted by Valarmathi et al. (2013a) revealed that an increase of spindle speed decreases the thrust force in drilling of MDF particleboard panels, whereas an increase of feed rate increases the thrust force de-veloped in drilling.

The value of the tool wear significantly affects (at $p = 0.000$) the process of delamination, using for assessment of the delamination the maximum radius of delaminated area at the hole exit R_{exit} (Fig. 7b). The opposite conclusion can be drawn with respect to the effect of the cutting speed.

The effect of cutting speed on the maximum radius of delaminated area is statistically in-significant (at $p = 0.221$). The situation is similar in the case of the effect of the feed rate, which influence is also statistically insignificant (at $p = 0.289$).

The delamination increases with increasing flank wear of a drill because the thrust force generated in drilling increases with increasing drill flank wear. The effect of drill wear on the delamination factor becomes significant at higher spindle speed (Chen 1997).
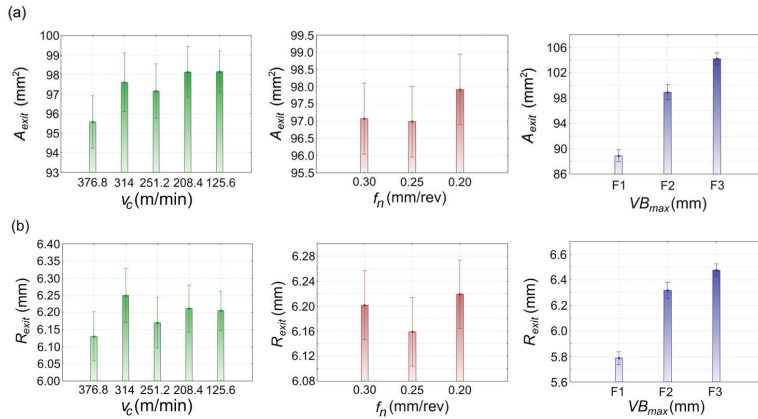

Fig. 7: Effect of cutting parameters and drill wear on the area of the delamination at the hole exit A_{exit} (a) and the maximum radius of delaminated area R_{exit} (b).

To summarise, the change in the cutting speed and feed rate does not significantly affect a maximum radius of delamination area R_{exit}. There was no statistically significant interaction between the analysed factors. The results of ANOVA analysis of the significance level of the effect of cutting speed, feed rate and signals both of cutting torque and thrust force on the factors of surface quality are presented in Tab. 3.

The effect of the cutting torque is statistically significant only in the case of one factor (A_{exit}) used to assess the quality of the machined surface. The effect of feed rate is statistically insignificant for the all factors and the cutting speed in the case of two factors A_{ent} and R_{ent} (see Tab. 3). The highest significance level was observed in the case of thrust force signal.

At the significance level $p = 0.000$ we can reject the hypothesis about the lack of effect of thrust force on the area of the delamination at the hole exit A_{exit} (Fig. 8a). Furthermore we can reject the hypothesis about the lack of the feed rate and cutting speed, at the significance level $p = 0.007$ and p = 0.030, respectively. Results are in good correlation with the findings of El-Sonbaty et al. (2004) who indicated that the thrust force and cutting torque increased with a drill diameter and feed rate, due to an increase in the shear area.

Tab. 3: The significance level of the wood machining parameters.

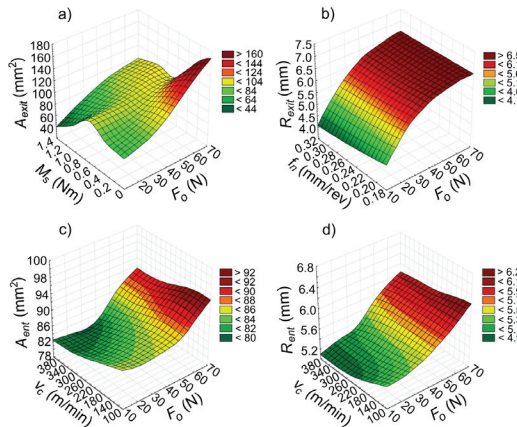| Variable	Significance level p			
	A_{ent}	A_{exit}	R_{ent}	R_{exit}
v_c	0.000	0.035	0.000	0.221
f_n	0.101	0.375	0.089	0.289
M_s	0.074	0.030	0.254	0.351
F_o	0.000	0.000	0.000	0.000

Fig. 8: Effect of thrust force F0, cutting speed vc and cutting torque Ms on the parameters of delamination: A_{exit} (a), R_{exit} (b), A_{ent} (c) and R_{ent} (d).

The results presented in Fig. 8b allow us to conclude that there is statistically significant (at p = 0.000) effect of thrust force and feed rate on the value of the maximum radius of the de-laminated area at the hole exit R_{exit}. The effect of cutting speed and thrust force on the value of parameters A_{ent} and R_{ent} is very similar (Fig. 8b, c). It is obvious that the drill thrust force decreases as the cutting speed increases (Gaitonde et al. 2008c). Lower machining forces im-ply slower tool wear, as the magnitudes of machining forces are expected to relate strongly with the tool wear rate (Lin et al. 2006). The experiments conducted by Hocheng and Tsao (2006) indicate that there is a critical thrust force, below which no damage occurs.

CONCLUSIONS

The tool life of drills during woodworking depends on many combinations of cutting pa-rameters and the wear of the drill blade. In this study, the effect of cutting parameters and tool wear factors on surface quality in the drilling process of a raw and melamine faced chipboard was studied. We have indicated that, in the drilling process of chipboard using through-holes and a carbide cemented drill, the surface quality of the hole depends mainly on the wear of tool flank VB_{max} and the cutting speed. With an increase of both cutting speed and feed rate, the tool life decreases and vice versa. However, in case of the cutting speed, this effect is larger.

Both a change in the cutting speed and wear significantly affects the area of the delamina-tion at the hole exit A_{exit}, while a change in the feed rate has no significant effect on A_{exit}. The

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effect of cutting torque is statistically significant only in the case of one factor (A_{exit}) used to assess the quality of the machined surface. The effect of feed rate is statistically insignificant for the all factors and the cutting speed in the case of two factors: the area of the delamination at the hole entry and maximum radius of delamination at the hole entry. The highest signifi-cance level was observed in the case of thrust force signal. The change in the cutting speed and feed rate does not significantly affect a maximum radius of delamination area at hole exit.

Statistical analysis of results using multifactor analysis of variance allows us to determine the relationship between drilling process parameters and tool wear. The feed rate and VB_{max} are the main factors that influence the value of the thrust force signal. Furthermore, the signal of cutting torque in high degree depends on cutting speed, feed rate and wear factor VB_{max}. The signals both of cutting torque and thrust force are highly correlated with the surface quality of the holes.

REFERENCES

1. Aguilera, A., Meausoone, P.J., Martin, P., 2000: Wood material influence in routing operations: the MDF case, Holz als Roh- und Werkstoff 58: 278-283.
2. Basturk, M.E., Guntekin, E., 2009: Effects of chitosan treatment on some particleboard properties, Wood Research 54(4): 91-98.
3. Benzeggagh, M.L., Kenane, M., 1996: Measurement of mixed mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus, Composites Science and Technology 49(4): 439-449.
4. Chen, W.C., 1997: Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates, International Journal of Machine Tools and Manufacture 37(8): 1097-1108.
5. Davim, J.P., Campos Rubio J., Abrão A.M., 2007a: Delamination assessment after drilling medium density fibreboard (MDF) using digital image analysis. Holzforschung, 61(3): 294-300.
6. Davim, J.P., Clemente, V.C., Silva, S., 2007b: Evaluation of delamination in drilling medium density fibre board, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 221: 655-658.
7. Davim, J.P., Gaitonde, V.N., Karnik, S.R., 2008: An investigative study of delamination in drilling of medium density fibre board (MDF) using response surface models, International Journal of Advanced Manufacturing Technology 37(1): 49–57.
8. Davim, J.P., Reis, P., 2003: Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study, Materials Design 24(5): 315-324.
9. El-Sonbaty, I., Khashaba, U.A., Machaly, T., 2004: Factors affecting the machinability of GFR/epoxy composites, Composite Structures 63(3-4): 329-338.
10. Feito, N., Diaz-Alvarez, J., Diaz-Alvarez, A., Cantero, J.L., Miguelez, M.H., 2014: Experimental analysis of the drill point angle and wear on the drilling of woven CFRPs, Materials 7(6): 4258-4271.

11. Gaitonde, V.N., Karnik, S.R., Campos Rubio, J., Esteves Correia, A., Abrão, A.M., Davim, J.P., 2008a: Analysis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites. Journal of Materials Processing Technology, 203: 431-438.

12. Gaitonde, V.N., Karnik, S.R., Davim, J.P., 2008b: Prediction and minimization of delamination in drilling of medium-density fiberboard (MDF) using response surface methodology and Taguchi design, Materials and Manufacturing Processes 23(4): 377–384.

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

14. Güler, C., Cöpür, Y., Böyüksari, U., 2009: Producing particleboards from hazelnut (*Corylus avellana* L.) husk and European black pine (*Pinus Nigra* Arnold), Wood Re-search 54(1): 125-132.

15. Hocheng, H., Tsao, C.C., 2006: Effects of special bits on drilling-induced delamination of composite materials. International Journal of Machine Tools and Manufacture, 46(12-13): 1403-1416.

16. Lin, R.J.T, van Houts, J., Bhattacharyya, D., 2006: Machinability investigation of medium-density fibreboard. Holzforschung, 60(1): 71-77.

17. Mehta, M., Reinhart, T.J., Soni, A.H., 1992: Effect of fastener hole drilling anomalies on structural integrity of PMR-15/gr composite laminates. In: Proceedings of the Machining Composite Materials Symposium, Chicago, USA.

18. Mercy, J.L., Prakash, S., Vijayalakshmi, P., Teja, P.V.S., 2014: Multi response optimization of drilling parameters during drilling of particle board using grey relational analysis. Applied Mechanics and Materials 592-594: 530-533.

19. 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.

20. Prakash, S., Palanikumar, K., 2011: Modeling for prediction of surface roughness in drilling MDF panels using response surface methodology, Journal of Composite Materials 45(16): 1639-1646.

21. Romoli, L., Dini, G., 2008: Experimental study on the influence of drill wear in CFRP drilling process. In: Proceedings of the 6th CIRP International Conference on Intelligent Computation in Manufacturing Engineering, Naples, Italy.

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

23. Valarmathi, T.N., Palanikumar, K., Sekar, S., 2013b: Parametric analysis on delamination in drilling of wood composite panels, Indian Journal of Science and Technology 6: 4347-4356.

24. Watson, P., Clauss, S., Ammann, S., Niemz, P., 2013: Fracture properties of adhesive joints under mechanical stresses, Wood Research 58(1): 43-56.

25. Zhao, H., Ehmann, K.F., 2002: Development and performance analysis of new spade bit designs. International Journal of Machine Tools and Manufacture, 42(13): 1403-1414.

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