DRILL WEAR DURING THE BORING OF PARTICLE BOARD: A MULTI-FACTOR ANALYSIS INCLUDING EFFECTS OF MINERAL CONTAMINANTS

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This paper evaluates and discusses multifactor non-linear, statistical dependencies of drill side-edges recession VB_K and drill diameter recession ΔD_W on the cutting path length L_C, the content of hard mineral contaminants C_{MC}, the size of contaminant particles S_{MC}, and the Mohs hardness M_H. Significant influence of the cutting path L_C, the content C_{MC} of hard mineral contaminants (HMC), and the size of contaminant particles S_{MC} was found, whereas the Mohs hardness M_H of the contamination particles was less important.

Keywords: Spiral drill; Side edges; Boring; Particle board; Cutting path; Content of hard mineral contamination; Size of contamination particles; Mohs hardness

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INTRODUCTION

The problem of machining mineral-contaminated particle board has been the subject of many studies from the point of view of the acceleration of tool wear. Hard mineral contamination (HMC) of particle boards has been recognized as the most important factor influencing cutting edge wear. However, the random distribution and variable content C_{MC} and size S_{MC} of the fractions of HMC, originated from the industrial manufacturing process for particle board has made it difficult to perform a qualitative and quantitative analysis of the influence of these factors (Porankiewicz and Grönlund 1991; Stühmeier 1989). More systematic, but still not complete studies of the wearing process of cutting tools have been enabled by artificial addition of different amounts of the HMC to laboratory-made particle board (Bridges 1971; Boehme and Münz 1987) and artificially adding different sizes, with the same amount of the HMC, to laboratory made fiber board (Kilinga and Back 1964). These studies achieved a more systematic evaluation of the wearing process of cutting tools. However, the evaluations cannot be considered complete, since these studies did not consider the effects of different contents of HMC together with differing sizes of contaminating particles, in a wide range of variation.

In the present study, a statistical analysis was performed for the dependencies of the side edge recession VB_K and the drill diameter recession ΔD_W on the content C_{MC}, the size S_{MC}, and the Mohs hardness of the HMC, as well as the cutting path length L_C, by boring laboratory-made particles boards that had been artificially contaminated at high levels of mineral (Szymański 2003).

EXPERIMENTAL

The present study is a reanalysis of data from the experiment performed in the Woodworking Machinery Laboratory, Agricultural University of Poznań, Poland, as described in an earlier publication (Szymański 2003). For machining tests a multispindel drilling machine DCWGW 19 (Fig. 1), employing a vertical position of working unit 1 was used. For work piece 3, clamping onto a machine working table 4 was achieved by use of two pneumatic cylinders 5.

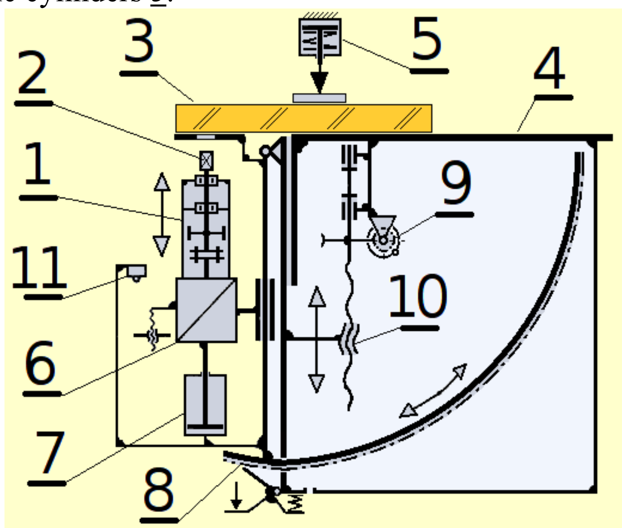

Fig. 1. Scheme of the multispindel drilling machine DCWGW 19: 1 - working unit, 2 - drill, 3 - work piece, 4 - working table, 5 - pneumatic cylinders for clamping, 6 - electrical motor, 7 - working unit feed pneumatic cylinder, 8 - latch mechanism, 9 - snail gear box, 10 - screw mechanism, 11 - end switch

Mechanical and physical properties of laboratory-made, urea-formaldehyde glue based particle boards

Short, two-edged spiral drills (Fig. 2.) equipped with a centering peak 3 and two side edges 2 and the cylindrical grip 5 were tested. The following machining parameters were applied (where the values in brackets “<   >” shows the minimum and maximum values of independent variables, and “ ..” marks show than many variables in a range were analyzed):

Board specifications:

- Density D = 636 < 601 .. 708 > kg/m^3, standard deviation SD = 21.8 kg/m^3.
- Moisture content mc = 8.02 < 7.9 .. 8.3 > %, SD = 0.05 %.

Material of the HMC:

- Electrocorunde EA (Al_20_3 94.5 – 97.3 %; $Ti0_2$ 2 – 4 %; $Si0_2$ 0.7 – 1.5 %), Mohs hardness M_H = 9.0.
- Carborunde SC (SiC 97 %; SiO_2 2 %; Fe_2O_3 0.2 %; C 0.2 %), Mohs hardness M_H = 9.2.

- Silica (SiO_2), Mohs hardness $M_H = 7.0$.

Average, total content of HMC: C_{MC} < 0.019; .. 15.54 % >.
Size of particles of the HMC, S_{MC} < 5 .. 650 μm >.

In the present study a quantifier describing the high temperature tribochemical reactions (HTTR) between the particle board tested and a binder of tool material, according to method described in works of Porankiewicz (2003a, 2003b) was not evaluated.

Machining parameters

- Spindle rotational speed $n = 2880$ min^{-1}.
- Maximum cutting speed $v_C = 1.13$ m/s.
- Feed speed $v_F = 0.8$ m/min.
- Feed per revolution $f_O = 0.3$ mm.
- Depth of an hole drilled $H_O = 12$ mm, $SD = 0.2$ mm.
- The holes were drilled perpendicularly to a wide surface of particle board specimen.

Parameters of the spiral, drill (Fig. 2)

- Total cutting path L_C < 1.131 .. 4298 m >.
- Number of holes drilled, for wear evaluation I_O < 1 .. 3800 >.
- Height of a side edges 2 $H_K = 1$ mm, $SD = 0.1$ mm.
- Height of the centering peak 3 $H_{KS} = 2.2$ mm, $SD = 0.1$ mm.
- Side edge recession measured in projection on a side working plane VB_{KF} < 0 .. 0.955 mm >.
- Side edge recession measured in bisector of wedge angle VB_{KW} < 0 .. 0.927 mm >.
- Maximum, main edge contour rake angle $\gamma_F = 13.73^o$, $SD = 1.47^o$.
- Maximum, main edge contour clearance angle $\alpha_F = 17.03^o$, $SD = 2.35^o$.
- Main cutting edge inclination angle in base (frontal) plain $\psi_R = 0^o$.
- Side edge wedge angle $\beta_K = 41^o$, $SD = 2^o$.
- Drill diameter $D_W = 8$ mm, $SD = 0.09$ mm.
- Recession of the drill diameter ΔD_W < 0 .. 0.056 mm >.
- Drill working part side axial and tangential taper 0^o.
- Stiffness of the drill mounted in the spindle $\varepsilon_D = 190$ N/mm, SD= 38 N/mm.
- Number of cutting edges $z = 2$.
- Material of the cutting edge was a high speed steel (HSS) type SW12C (T grade).
- Hardness of the drill material (64-66 HRC).

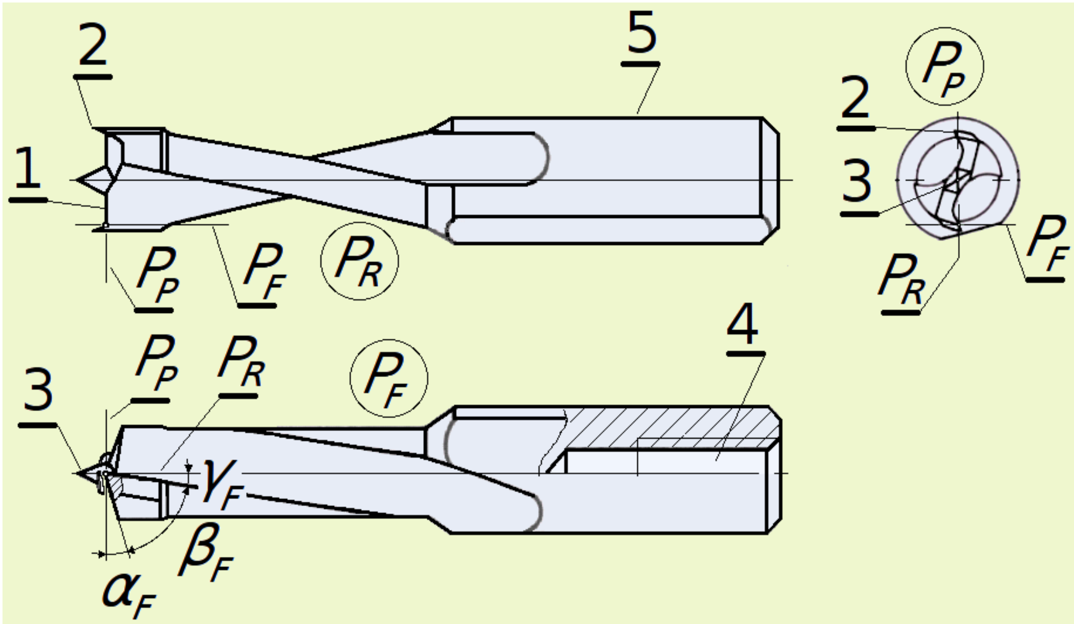

Fig. 2. Stereometrical parameters of the drill; 1 - main (face) cutting edge, 2 - side edge, 3 - centering peak, 4 - hole notched for fixing screw, 5 - cylindrical grip

A small sharpness angle $\beta_K = 41^o$ of the side edges was necessary in order to achieve a narrow indentation of a surface cut, in order to protect a hole edge against large damage that may be caused by the following action of the main cutting edge. The side edge recession was measured in relation to a base mark (scratch) made on a side surface of the drill on a screen of a tool microscope BMI-I, under 50X magnification, with accuracy of 0.005 mm. The side edge recession V_{BKF} was measured in the direction parallel to the axis of the drill. The side recession V_{BKW} was measured in the direction of the bisector of the sharpness angle. The drill axis was positioned perpendicularly to the optical axis of the microscope. The recession of the diameter of the drill was measured with use of a passameter TPI with an accuracy of 0.002 mm. The recessions VB_K and ΔD_W were measured after drilling a number of holes I_O. Use of the number I_O made it possible to evaluate the cutting path according to formula (1).

$$L_C = \frac{I_O(H_O + H_K - VB_{KF})}{f_O}\sqrt{(\Pi D_W)^2 + f_O^2}\,0.001 \text{ (m)} \tag{1}$$

In formula (1) the new term is I_O is the number of holes drilled.

A statistical model of the relations $VB_{KF} = f(L_C, C_{MC}, S_{MC}, M_H)$, $VB_{KW} = f(L_C, C_{MC}, S_{MC}, M_H)$, and $\Delta D_W = f(L_C, C_{MC}, S_{MC}, M_H)$ should fit the experimental matrix with the lowest summation of residuals square *SK*, by the lowest *SD*, and by the highest correlation coefficient *R* between predicted and observed values. It is also very important to get a proper influence of the variables analyzed, especially in the case of an incomplete experimental matrix. Usually the use of a simpler model results in reduced approximation quality (larger *SK* and *SD,* and lower *R*) and also may reverse the impact of variables having lower importance. It has also to be pointed out that the statistical relationship is valid only for ranges of independent variables chosen in the experimental matrix. For some functions, especially those evaluated for an incomplete experimental matrix, points lying outside the analyzed range of independent variables usually are subject to significant error. In the authors' opinion additional justification for a choice of a certain type of function make sense when several experiments have been done already under the same machining conditions.

In the evaluation process of statistical dependencies $VB_{KF} = f(L_C, C_{MC}, S_{MC}, M_H)$, $VB_{KW} = f(L_C, C_{MC}, S_{MC}, M_H)$, and $\Delta D_W = f(L_C, C_{MC}, S_{MC}, M_H)$ as linear functions, second order multinomial formulas, as well as power type and exponential functions without and with interactions, were analyzed in preliminary calculations. The most adequate models, according to assumptions made, appeared to be those represented by equations (2) through (4). Estimators for formulas (2) and (3) were evaluated from an incomplete experimental matrix containing 485 measuring points. Model (4) was evaluated from an incomplete experimental matrix containing 387 measuring points. The drill diameter recession was not measured exactly after the same tests performed for the side cutting edge recession. During the evaluation process of all models, elimination of unimportant or low-import estimators was carried out by use of coefficient of relatively importance C_{RI}, defined by formula (5), by assumption $C_{RI} > 0.1$.

$$VB_{KF} = a_1 \bullet L_c^{a_2} \bullet C_{MC}^{a_3} \bullet S_{MC}^{a_4} \bullet M_H^{a_5} + a_6 \bullet L_C^{a_7} \bullet C_{MC}^{a_8} + a_9 \bullet L_C^{a_{10}} \bullet S_{MC}^{a_{11}} + a_{12}$$

$$0 < VB_{KF} < 0.955 \ mm \qquad (2)$$

$$VB_{KW} = b_1 \bullet L_c^{b_2} \bullet C_{MC}^{b_3} \bullet S_{MC}^{b_4} \bullet M_H^{b_5} + b_6 \bullet L_C^{b_7} \bullet C_{MC}^{b_8} + b_9 \bullet L_C^{b_{10}} \bullet S_{MC}^{b_{11}} + b_{12}$$

$$0 < VB_{KW} < 0.927 \text{ mm} \qquad (3)$$

$$\Delta D_W = c_1 \bullet L_c^{c_2} \bullet C_{MC}^{c_3} \bullet S_{MC}^{c_4} \bullet M_H^{c_5} + c_6 \bullet L_C^{c_7} \bullet C_{MC}^{c_8} + c_9 \bullet L_C^{c_{10}} \bullet S_{MC}^{c_{11}} + c_{12}$$

$$0 < \Delta D_W < 0.056 \text{ mm} \qquad (4)$$

$$C_{RI} = \frac{SK - SK_{OK}}{SK} \bullet 100 \quad (\%) \qquad (5)$$

In formula (5) the new terms are SK_{0K}, which is the summation of square of residuals, by estimator $a_K = 0$, as well as a_K, which is the K estimator in the statistical model.

The summation of residuals square SK, the standard deviation SD and the square of correlation coefficient of the predicted and observed values, R^2, were used for characterization of approximation quality. Calculations were performed at Poznań Networking & Supercomputing Center (PCSS) on a SGI Altix 3700 machine, using an optimization program, based on a least squares method combined with gradient and Monte Carlo methods (Porankiewicz 1988), with further changes.

RESULTS AND DISCUSSION

The following estimators for formula (2), describing the dependence $VB_{KF} = f(L_C, C_{MC}, S_{MC}, M_H)$ resulted from the evaluation: a_1 = 2.04531, a_2 = 0.48774, a_3 = 0.32370, a_4 = 0.5633, a_5 = 0.5723, a_6 = 13.6559, a_7 = 0.7409, a_8 = 0.9444, a_9 = -0.5439, a_{10} = 0.3149, a_{11} = 1.6801. The approximation quality of the fit of the model (2) can be characterized by quantifiers: SK = 0.57, R = 0.98; R^2 = 0.96; SD = 0.034, and was also illustrated in Fig. 2a. The coefficients of relatively importance C_{RI} for estimators of formula (3) were as follows: C_{RI1}= 2366, C_{RI2}= 39682, C_{RI3} =17420, C_{RI4} = 21133, C_{RI5} = 1162, C_{RI6} = 1084, C_{RI7} = 277, C_{RI8} = 17, C_{RI9} = 42, C_{RI10} = 30, C_{RI11} = 25.

The following estimators for formula (3), describing the dependence $VB_{KW} = f(L_C, C_{MC}, S_{MC}, M_H)$ were determined from the evaluation: b_1 = 1.3751, b_2 = 0.5446, b_3 = 0.41, b_4 = 0.5124, b_5 = 0.8754, b_6 = 9.3458, b_7 = 0.6696, b_8 = 0.8817, b_9 = $2.14 \cdot 10^{-5}$, b_{10} = 1.4997, b_{11} = -1.4024. The approximation quality of the fit of the model (2) can be characterized by quantifiers: SK = 0.6; R = 0.98; R^2 = 0.96; SD = 0.036, and was also illustrated in Fig. 2b. The coefficients of relatively importance C_{RI} for estimators of formula (3) were as follows: C_{RI1}= 1959, C_{RI2}= 50243, C_{RI3} = 38068; C_{RI4} = 13378, C_{RI5} = 1397, C_{RI6} = 936, C_{RI7} = 333, C_{RI8} = 56, C_{RI9} = 8, C_{RI10} = 1, C_{RI11} = 8.

The following estimators for formula (4), describing the dependence $\Delta D_W = f(L_C, C_{MC}, S_{MC}, M_H)$ were determined : c_1 = 14.6448, c_2 = 1.7372, c_3 = 1.5072, c_4 = 0.5123, c_5 = 1.2765, c_6 = -109.8472, c_7 = 0.7053, c_8 = 4.1676, c_9 = $-3.63 \cdot 10^{-8}$, c_{10} = 1.3028, c_{11} = -2.1986, c_{12} = 0.00166. The approximation quality of the fit of the model (2) can be characterized by quantifiers: SK = 0.007, R = 0.96, R^2 = 0.91, SD = 0.004, and was also illustrated in Fig. 2c. The coefficients of relatively importance C_{RI} for estimators of formula (3) were as follows: C_{RI1}= 1251, C_{RI2}= $7.15 \cdot 10^7$, C_{RI3} = $1.58 \cdot 10^{10}$, C_{RI4} = 22970, C_{RI5} = 986, C_{RI6} = 4, C_{RI7} = 4, C_{RI8} = 52563, C_{RI9} = 53, C_{RI10} = 9, C_{RI11} = 53, C_{RI12} = 12.

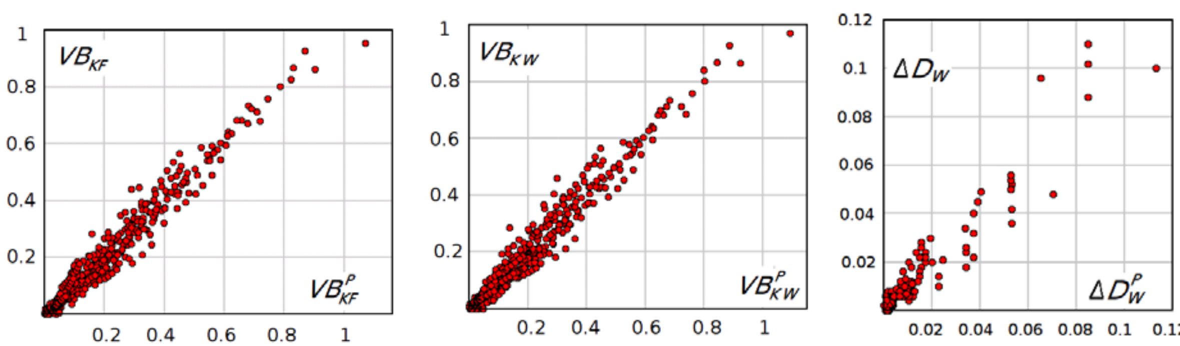

Fig. 3. Plots of observed side edge recessions VB_{KF}, VB_{KW}, and recession of drill diameter ΔD_W against predicted values according to models (2), (3), and (4)

The plots of predicted values from formulas (2), (3), and (4) against the observed values, as shown in Fig. 3, suggested the presence of unrecognized systematic variation, which fell with increases of the VB_K and ΔD_w recession values. This variation could be generated by the HTTR factor, which was not evaluated in the analyzed experiment.

Figures 4 and 5 show that the side edge recessions VB_{KF} and VB_{KW} strongly depended upon the content of hard mineral contaminants C_{MC} and the size of the contaminant particles S_{MC}. An increase in the content of mineral contamination C_{MC} and the size of contamination particles S_{MC} parabolically decreased enlargement of the side edge recessions VB_{KF} and VB_{KW}.

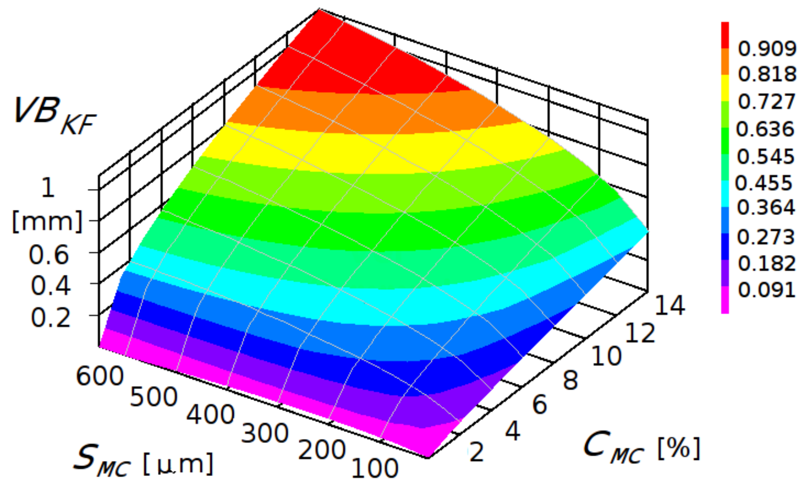

Fig. 4. The plot of relation between side edge recession VB_{KF} and the content of mineral contamination C_{MC} and the size of mineral contamination particles S_{MC}, according to model (2)

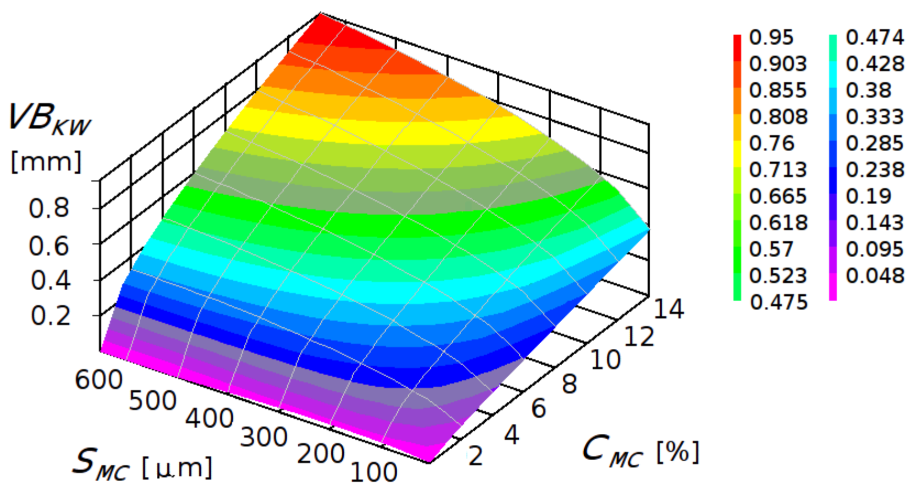

Fig. 5. The plot of relation between side edge recession VB_{KW} and the content of mineral contamination C_{MC} and the size of mineral contamination particles S_{MC}, according to model (3)

For the smallest value of S_{MC} the relationships VB_{KF} and $VB_{KW} = f(C_{MC})$ were well visible, which was in agreement with results of previous work (Porankiewicz 2003a, 2003b) and also in contradiction with other information from the literature, suggesting a lack of such dependence (Boehme and Münz 1987; Sparks and Taylor 1981; Stühmeier 1989). For the smallest values of the C_{MC} and the largest values of the S_{MC} >300 µm this relation disappeared. However for smaller contaminant particles at S_{MC} = 200 µm and the lowest content of mineral contaminants C_{MC}, a local small maximum of the VB_{KF} and the

VB_{KW} values was observed. This phenomenon was in agreement with earlier work (Porankiewicz 2003b). A scarcity of contaminant particles within the size range S_{MC} < 111; 275 μm > in the experimental matrix was a possible reason that the local maximum disappeared for larger content of mineral contamination C_{MC}.

Figures 6 and 7 show that the side edge recessions VB_{KF} and VB_{KW} strongly depended upon the total cutting path L_C. With increasing total cutting path L_C there was a parabolically decreasing manner of growth in the side edge recessions VB_{KF} and VB_{KW}. The influence of Mohs hardness M_H, on the side edge recessions VB_{KF} and VB_{KW} was less significant, and it was observed only from a certain length of the cutting path L_C. An enlargement of the Mohs hardness M_H, for the largest cutting path L_C, slightly increased the side edge recessions VB_{KF} and VB_{KW}. This phenomenon contradicts information from the work of Kilinga and Back (1964).

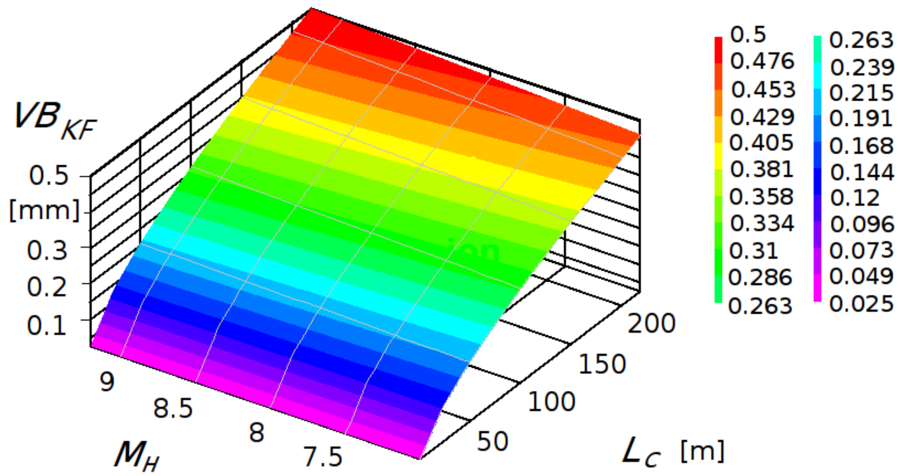

Fig. 6. Plot of relation between the side edge recessions VB_{KF} and the total cutting path L_C and the Mohs hardness M_H, according to model (2)

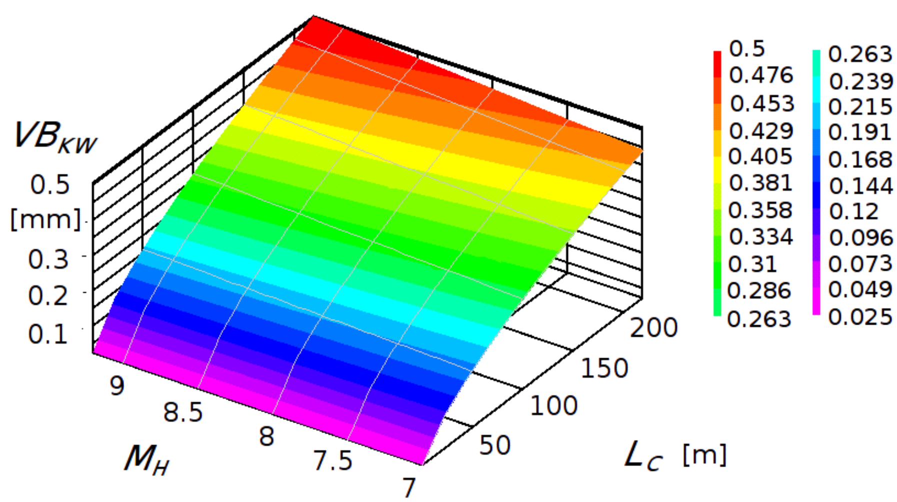

Fig. 7. Plot of relation between the side edge recession VB_{KW} and the total cutting path L_C and the Mohs hardness M_H, according to model (3)

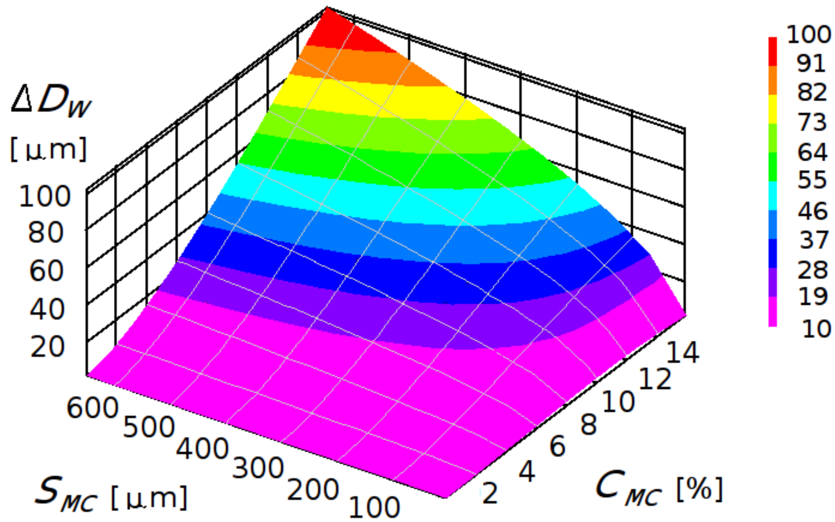

Fig. 8. Plot of relation between the drill diameter recession ΔD_W and the content of hard mineral contamination C_{MC} and the size of hard mineral contamination S_{MC}, according to model (4)

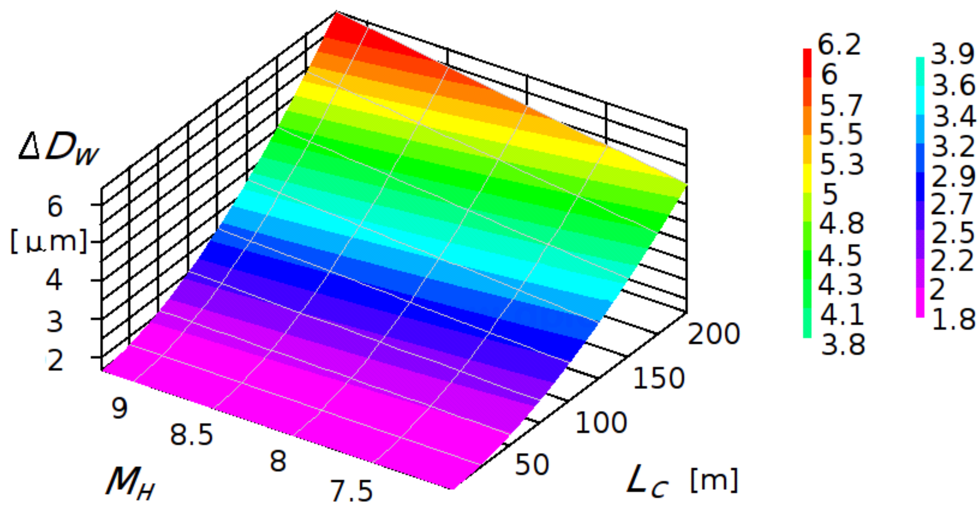

Fig. 9. Plot of relation between the drill diameter recession ΔD_W and the total cutting path L_C, and the Mohs hardness M_H, according to model (4)

The reason for the contradiction concerning the role of hardness of the HMC particles on the VB_K and ΔD_W recessions observed in the present analysis, in comparison with the literature, was probably the limited amount of data analyzed in the cited work (Klinga and Back 1964), as well as the indirect cutting edge wear measurements (by means of the cutting power). More work is needed to explain this phenomenon.

Figure 8 shows that the drill diameter recession ΔD_W strongly depended upon the content of mineral contaminants C_{MC} and the size of particles of the HMC S_{MC}. Looking at the dependency of the drill diameter recession ΔD_W on the content C_{MC} of the HMC for the largest S_{MC} (Fig. 8), it can be seen that there was an increasing tendency in a parabolically increasing manner. This trend decreased with decreasing size of the contaminant particles C_{MC} and disappeared for S_{MC} as high as about 100 μm. For S_{MC}

smaller than about 100 μm this relation changed to a parabolically decreasing one. The increase of the size of contamination particles S_{MC} increased the side edge recession ΔD_W in a parabolically decreasing manner.

Figure 9 shows that the drill diameter recession ΔD_W strongly depended upon the total cutting path L_C. An enlargement of the total cutting path L_C increased the drill diameter recession ΔD_W in a parabolically increasing manner. The influence of Mohs hardness M_H, on the recession of drill diameter was less significant, and it was only observed starting from a certain length of the cutting path L_C. An enlargement of the Mohs hardness M_H slightly increased the drill diameter recession ΔD_W.

There were non-linear increases in the impacts of the content C_{MC} and the size S_{MC} of the HMC, together with the numbers of holes drilled I_O, expressing the total cutting path L_C, on the side edge VB_K and the drill diameter ΔD_W recessions. These factors appeared to be the most important in the analyzed experiment. A parabolically increasing tendency of the influence $\Delta D_W = f(C_{MC})$ for S_{MCI} larger than about 100 μm and $\Delta D_W = f(L_C)$ are new findings, relative to the literature. The large range of variation of the content C_{MC} and the size S_{MC} of the HMC in the analyzed work probably made it possible to achieve this result.

An abrasion mechanism seems to be dominant in the wear of drills. However, this may not necessarily be true in all cases. Starting from a certain value of the cutting path L_C, the HTTR may contribute to the total wearing mechanism in the analyzed case, which involved hidden cutting. This is because, in the experimental work considered, the effect of high temperature corrosivity of laboratory-made particle boards on the HSS tool material was not evaluated, lying outside the scope of the present paper.

It has to be mentioned that the experimental samples that were analyzed in this paper (Szymański 2003) were planned incorrectly from point of view of maximum content of mineral contamination C_{MC}. According to many studies (Porankiewicz and Grönlund 1991; Sparks and Taylor 1981; Stühmeier 1989), the maximum artificial HMC level observed in industrial manufactured particle board did not exceed 8000 mg/kg (0.8 %), and in solid wood the HMC originating from rainforests did not exceed 45000 mg/kg (4.5 %) (Amos 1952). Moreover, in several works (Kilinga and Back 1964; Bridges 1971; Boehme and Münz 1987) examining laboratory-made, artificially highly contaminated particle board, the content of hard mineral contamination C_{MC} did not exceed 10000 mg/kg (1 %). The HMC of drilled skin layer also was not evaluated in that experiment (Szymański 2003), in order to show real, maximum C_{MC}, which might even be 1.5 times greater than the applied total average C_{MC}. The choice of the HSS tool material for machining of ultra-highly mineral contaminated particle board also looks very strange. A cemented carbide tool material ought to be examined in this kind of experiment. It is suggested that such considerations could be included in future studies.

CONCLUSIONS

1. The side edge recessions VB_{KF} and VB_{KW} strongly depended upon the cutting path L_C. An increase of the the cutting path L_C increased the side edge recession VB_{KF}, but the magnitude of the effect fell off in a parabolically decreasing manner.
2. The side edge recessions VB_{KF} and VB_{KW} strongly depended upon the content of hard mineral contaminant C_{MC}. An increase of the content of hard mineral contaminant C_{MC} increased the side edge recession VB_{KF}, but again the effect fell off in a parabolically decreasing manner.
3. The side edge recession VB_{KF} and VB_{KW} strongly depended upon the size of particles of hard mineral contaminants S_{MC}. An increase of the size of particles of hard mineral contaminants S_{MC} increased the side edge recession VB_{KF}, and the effect fell off in a parabolically decreasing manner.
4. The recession of the drill diameter ΔD_W strongly depended upon the cutting path L_C. An increase of the the cutting path L_C parabolically increased, in a parabolically increasing manner, the drill diameter recession ΔD_W.
5. The recession of the drill diameter ΔD_W strongly depended upon the the content of hard mineral contaminant C_{MC}. An increase of the content of hard mineral contamination C_{MC} parabolically increased the drill diameter recession ΔD_W in the case of particles of hard mineral contaminants S_{MC} that were larger than about 100 μm.
6. The recession of the drill diameter ΔD_W strongly depended upon the size of hard mineral contaminants S_{MC}. An increase of the size of particles of hard mineral contamination S_{MC} parabolically increased the drill diameter recession ΔD_W in a parabolically decreasing manner.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Poznań Networking & Supercomputing Center (PCSS) calculation grant.

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Article submitted: Feb. 8, 2008; Peer review completed: March 21, 2008; Revised article received: March 22, 2008; Accepted with final revisions. March 25, 2008; Published: March 26, 2008.