Statistical Evaluation of Impact of Technological Factors on Surface Texture of WPC Composites

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The paper aims at evaluating the impact of technological parameters of a drilling process on the parameter of surface roughness Rz (maximum height of roughness profile) of wood-based material (WPC – Wood Plastic Composite). During drilling with tools 3.0, 5.0 and 7.0 mm in diameter, the spindle speed n_c and feed rate f were changed. The evaluation of statistical significance was performed using the ANOVA mathematical tool (two-way with repetition). Using a simple conversion, it is possible to assess which of the set parameters affects the final surface quality, which serves as supporting information for the work of an engineer.

Keywords: statistical evaluation, composite, surface texture

WPC materials are formed by combining two substances – discontinuous reinforcement (wood particles, or cellulose microfibers) and a continuous binder (plastic matrix), in a certain proportion. The final properties of the product depend on the ratio of individual phases and the method of production. The components are mixed under the influence of heat, and through the use of an extrusion head of a press obtain their required shape, size. Composites with natural reinforcements replace traditional wood in flooring industry, in the field of garden furniture, pallets, construction, but their representation they also found in dynamic automotive production (door panels, dashboard components, etc.) [1]. Presence of wood in the plastic matrix increases the strength (and stiffness), and reduces the cost of materials. Unlike the plastic products, they are referred to as *"friendly environment"*, because it is possible to use in their production besides the original plastic material also recycled plastic (from PVC bottles), or the waste from wood processing industry (wood flour, sawdust). Assumptions for the use in the future: with the increasing application of those materials, also secondary processing should be considered. Despite the used manufacturing technologies, there are many reasons for the application of classical machining (number of technological operations can be reduced to: grinding, drilling and finishing operations which currently can be performed on just one CNC machining center) and thus focus attention to emerging machined surfaces, the tools used, their wear, dimensional accuracy and set technological parameters of the process. Buehlmann (2011) compares the tool wear after grinding and routing five samples of commercially purchased wood composites with a comparative sample (white pine). The author registers a lower degree of wear of conventional wood and assumes that the increased wear of tools for machining WPCs was due to their composition (the pigments to achieve the desired shade) [2]. The authors [3] describe WPC machined surfaces after cutting, and the temperature arising in connection with the change of cutting depth, speed, width of cut and the feed rate. They state that due to the low softening point of wood composites, it is necessary to keep the temperature as low as possible during the cutting operation. The publication by Guo XL. et al. (2010) describes the relationship between the speed of cutting when sawing and the quality of machined surfaces of three samples of WPCs with a different matrix (PE/PP/PVC + rice hull flour). The results show that the spindle speed has significant effects on the surface quality of the machined samples. The advantage of using a high cutting speed in sawing WPCs is evident [4]. The publication of authors Šomšáková et al. describes the quality of machined surfaces after turning with a monolithic tool from HSS when changing the feed rate of machining (for a constant cutting speed and depth of cut). In conclusions, there is a formulated consideration related to following research in the given field and the recommendation to set a lower feed rate and select tools with a large radius of curvature (for turning) [5, 6]. From the perspective of an engineer in machining in general, it is necessary to specify which of the parameters set has effect on the machining, and in contrary, which can be corrected (changed) without its influence to be crucial. In case of the experimental assessment mentioned below, a mathematical model was specified to assess the significance of the impact of technological parameters during the operation of machining (with respect to the quality parameter of surface – the greatest height of profile inequalities).

Experimental part

Materials and methods

A composite material with wooden reinforcement and a HDPE matrix in a ratio 30:70 % (matrix: reinforcement). A machined profile manufactured by extrusion, size 60 x 40 x 3600 mm. Mechanical properties of the composites were determined in the laboratories of VÚHZ Dobrá. Tensile testing (table 1) was made in accordance with ISO 6892-1, with a constant load speed of 0.015 $mm \cdot s^{-1}$ (uncertainty ± 0.8 %), three-point bending test (table 2) carried out in accordance with ISO 178-1, with a constant load velocity of 0.08 $mm \cdot s^{-1}$ (uncertainty ± 1 %). The samples were taken from the middle part of the profile, in the direction of the axis of extrusion. The images captured in figure 1 were

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No. of sample	Ultimate tensile strength [MPa]	Elongation at rapture [%]	Reduction [%]	Deformation work [mJ]
1	24	2.8	2.0	20.4
2	15	2.9	0.4	12.4
3	24	3.4	0.8	24.1
4	15	5.1	0.4	13.5
5	* defects			

* Probably by reason of the occurance of defects, the test sample 5 was already torn at 200 N, so the result is not mentioned. The yield point could not be determined correctly as for the given type of material, any conventional values of agreed deformation are not available for the determination of bland yield point.

Table 1
VALUES OF MECHANICAL PROPERTIES AFTER THE TENSILE TEST

No. of sample	Ultimate bending strength [MPa]	Deformation work [mJ]
1	18.76	1.01
2	15.69	0.92
3	16.71	0.90
4	15.44	0.80
5	17.13	0.92

Table 2
VALUES OF MECHANICAL PROPERTIES AFTER THE TENSILE TEST

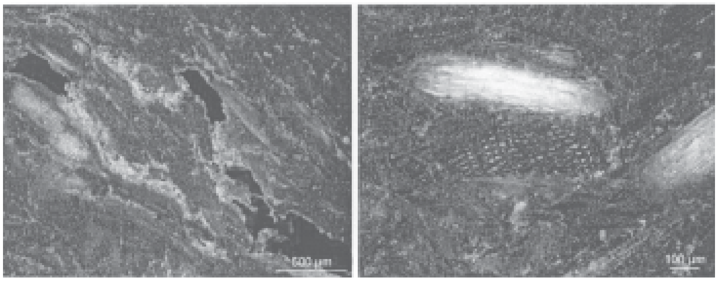

Fig. 1. An image from the optical microscope Nikon Eclise 80i; a microscopic structure of the WPC material used in the experiment (samples taken from the front of the extruded profile – prior to machining)

taken from the front of the extruded profile prior to machining, in the dark matrix of the material, narrow wood chips, from tens of micrometers to about 2 mm in length, are visible (particles are completely or partially supersaturated with polymer). The material comprises micro-cracks localized in the area of a wood-plastic contact. Isolated cracks (size 20 µm to 4 mm) pass even trough wood chips in the direction of their longitudinal axis. Particles are unevenly distributed throughout the volume of the material. Orientation of wood particles follows the flow of the polymer.

In the drilling operation, TiN coated HSS drill bits were used, diameters: from 3.0, 5.0 and 7.0 mm (lengths of cutting part l_3=33 mm, l_5=52 mm, l_7=69 mm, point angles ε_r=118° and inclination angles λ=30°); the cutting of the semi-finished product to the required length dimensions (40 x 60 x 230 mm) was made using the ERGONOMIC 275.230 DG frame saw; holes made by means of the CNC vertical 3-axis machining center Pinnacle VMC 650S. The machining process was carried out without cutting media (due to the natural composite reinforcement), made holes open, a drilling cycle with irrigation. During machining, two parameters were changed – the feed rate *f* and the speed of spindle n_c. For each set cutting conditions, 3 holes were made (fig. 2 and table 3). To measure the parameters of surface roughness, the MITUTOYO SJ-400 device with contact operation was used with the automatic compensation of radius and inclination, an evaluation length l_r = 4.0 mm (filter profile λ_c = 0.8 mm). Prior to measurement, the samples were divided along the holes; surface roughness was measured at a distance of 20 mm from the beginning of the hole on the right and on the left sides with repeating 3 times. The values entered in table 5 represent arithmetic averages of 3 measurements of the right and the left sides of a marginal and an inner hole.

After drilling the holes along the extruded profile, it is possible to assess the significance of the impact of the changed technological parameters on the surface texture by applying the ANOVA tool – two factors with repetition (a built mathematical model of a spreadsheet that performs calculations based on the deviation between the values of a particular variable). Considering the fact that this is an application of sole technology for one type of workpiece (when changing the diameters of a drill bit), it can be assumed that in all three cases, the result is the same, and thus the impact of the input factors being changed on the final characteristics will be the same.

Assesing the level of impact of each variable parameters on the outcome assessed parameter of surface roughness *Rz* was performed using the ANOVA analytical tool – two factors with repetition (a built mathematical model of a spreadsheet that performs calculations based on the deviation between the values of the variable). The parameter *Rz* is a dependent variable *Y*, the feed rate and

Spindle speed n_c [rpm]	2000	4000	6000	2000	4000	6000	2000	4000	6000
Feed rate *f* [mm·min^{-1}]	100	100	100	200	200	200	300	300	300
Hole making	1	2	3	4	5	6	7	8	9

Table 3
CONDITIONS OF CUTTING PROCESS

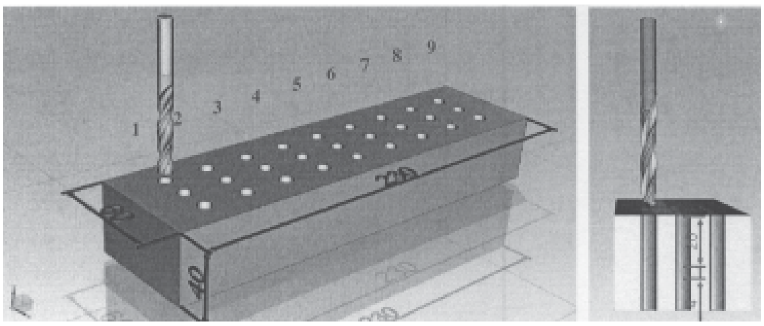

Fig. 2. Marking the holes under the conditions of the cutting process; the marked length of the evaluated section *l*=4.0 mm (cut along the holes)

Y_{ijk}	Factor *b* (feed rate)			$Y_{i\bullet\bullet}$
	j=1	...	*j=b*	
i=1	Y_{111} Y_{112} . $\rightarrow Y_{11\bullet}$. Y_{11m}	...	Y_{1b1} Y_{1b2} . $\rightarrow Y_{11\bullet}$. Y_{1bm}	$Y_{1\bullet\bullet}$
Factor *a* (spindle speed)	. . . .	...	. . . .	. . . .
i=a	Y_{a11} Y_{a12} . $\rightarrow Y_{a1\bullet}$. Y_{a1m}	...	Y_{ab1} Y_{ab2} . $\rightarrow Y_{ab\bullet}$. Y_{abm}	$Y_{a\bullet\bullet}$
$Y_{\bullet j\bullet}$	$Y_{\bullet 1\bullet}$	...	$Y_{\bullet b\bullet}$	$Y_{\bullet\bullet\bullet}$

Table 4
MATRIX OF CALCULATION

a=3 number of changed spindle speeds (2000, 4000, 6000 rpm)
b=3 number of changed feed rates (100, 200, 300 mm.min^{-1})
m=4 number of measurements under individual specified conditions
N=36 total number of values of the variable *Y* mentioned in the matrix of the experiment (as the product of the previous three: *a'* . *b* . *m*)

	Feed rate *f* [mm·min^{-1}]		
Speindle speed n_c [rpm]	**100**	**200**	**300**
2000	14.400	14.267	18.800
	11.800	11.967	25.033
	11.933	15.700	12.933
	12.667	19.167	14.933
4000	21.367	26.966	17.733
	13.133	14.067	18.100
	16.767	15.700	18.633
	15.933	19.167	17.400
6000	23.267	21.533	35.900
	23.200	19.933	14.700
	29.567	23.200	22.400
	31.600	27.467	13.267

Table 5
VALUES OF THE PARAMETER *Rz* SUBSTITUED TO THE MATRIX (A TOLL DIAMETER OF 7.0 mm)

the spindle speed are factors *A*, *B*. The variable *Y* has its variability measured by the sum of squares of deviations from the total average. At the beginning of the analysis, a basic assumption is pronounced and that is – the variability of values of the variable *Y* is affected by the factor *A*, or by the factor *B* (or by their interaction). The factor A has levels: $a_1, a_2, a_3, \dots a_a$. The factor *B* has *b* levels: $b_1, b_2, b_3, \dots b_b$. At each desired level, multiple replications can be performed. The basic consideration results from the total of sums of squares caused by individual levels, their interactions, or by the influence of residues and errors:

$$SS_{TOT} = SS_A + SS_B + SS_{AB} + SS_E \qquad (1)$$

where:
SS_{TOT} – total sum of squares (Sum of Squares)
SS_A – sum of squares caused by level A (impact of level A)
SS_B – sum of squares caused by level *B* (impact of level *B*)
SS_{AB} – sum of squares caused by interactions of levels *A* and *B*
SS_E – sum of squares caused by effect of residues, errors, etc.

In the resulting tables (table 6 to table 8) for individual tools, the values are obtained, based on which it is assessed whether the specified factors (or their interactions) influence the final variable *Y* or not. The values acquired by means of the ANOVA tool can be calculated manually using the matrix in table 4 [7].

Through the matrix, standard deviations of individual levels are calculated (SS_A – in the table of the ANOVA analytical tool referred to as Selection, $SS_B \rightarrow$ referred to as Columns, $SS_{AB} \rightarrow$ referred to as Interaction). Calculating $\sum_{ijk} y_{ijk}^2 = 14126.51$ and y = 680.4, thus the total sum of squares is as follows:

$$SS_{TOT} = \sum_{ijk} y_{ijk}^2 - \frac{y_{...}^2}{N} = 14126.51 - \frac{680.4^2}{36} = 1266.955 \qquad (2)$$

Calculating $\sum_{ij} y_{ij.}^2 = 53791.730$; subsequently SS_T:

$$SS_T = \frac{1}{m} \cdot \sum_{ij} y_{ij.}^2 - \frac{y_{...}^2}{N} = \frac{1}{4} \cdot 53791.730 - \frac{680.4^2}{36} = 588.373 \qquad (3)$$

Source of variabilty	SS	Dif.	MS		F	Value P	F_{krit}
Selection	469.333	2	234.667	×	**9.33712**	0.00083	3.35413
Columns	1.16954	2	0.58477	×	0.02327	0.97702	3.35413
Interaction	117.871	4	29.4677	×	1.17249	0.34498	2.72777
Together	678.581	7	25.1326				
Total	1266.96	35					

Table 6
EVALUATION OF THE EFFECT OF INDIVIDUAL FACTORS – *A*, *B* ON THE PARAMETER OF SURFACE ROUGHNESS, 7.0 MM DIAMETER TOOL (*DIF.* = *DIFFERENCE*)

Source of variabilty	SS	Dif.	MS		F	Value P	F_{krit}
Selection	156.672	2	78.3362	×	**3.14532**	0.05947	3.35413
Columns	266.407	2	133.204	×	5.34833	0.01105	3.35413
Interaction	15.9182	4	3.97956	×	**0.15979**	0.95680	2.72777
Together	672.453	7	24.9057				
Total	1111.45	35					

Table 7
EVALUATION OF THE EFFECT OF INDIVIDUAL FACTORS – *A*, *B* ON THE PARAMETER OF SURFACE ROUGHNESS, 5.0 MM DIAMETER TOOL (*DIF.* = *DIFFERENCE*)

Source of variabilty	SS	Dif.	MS		F	Value P	F_{krit}
Selection	141.247	2	70.6232	×	**1.70623**	0.02005	3.35413
Columns	77.9036	2	38.9518	×	**0.94106**	0.40264	3.35413
Interaction	357.791	4	89.4476	×	**2.16102**	0.10056	2.72777
Together	1117.57	7	41.3915				
Total	1694.51	35					

Table 8
EVALUATION OF THE EFFECT OF INDIVIDUAL FACTORS – *A*, *B* ON THE PARAMETER OF SURFACE ROUGHNESS, 3.0 MM DIAMETER TOOL (*DIF.* = *DIFFERENCE*)

Calculating $\sum_i y_{i..}^2 = 159946.700$ and $\sum_j y_{.j.}^2 = 154328.800 \rightarrow$ the calculation of the sum of squares caused by the level *A*: SS_A, the sum of squares caused by the level *B*: SS_B, the sum of squares caused by their interaction SS_{AB}, and the sum of squares caused by the influence of residues SS_E:

$$SS_A = \frac{1}{bm} \cdot \sum_i y_{i..}^2 - \frac{y_{...}^2}{N} = \frac{1}{12} \cdot 159946.7 - \frac{680.4^2}{36} = 469.333 \quad (4)$$

$$SS_B = \frac{1}{am} \cdot \sum_j y_{.j.}^2 - \frac{y_{...}^2}{N} = \frac{1}{12} \cdot 154328.8 - \frac{680.4^2}{36} = 1.169 \quad (5)$$

Based on SS_T, SS_{TOT}, the values SS_{AB} and SS_E are determined:

$$SS_{AB} = SS_T - SS_A - SS_B = 117.871 \quad (6)$$
$$SS_E = SS_{TOT} - SS_T = 678.581 \quad (7)$$

Calculating the degrees of freedom (in the table of ANOVA analytical tool referred to as *Differnece*) is as follows:

$$df_A = a - 1 = 2$$
$$df_B = b - 1 = 2 \quad (8)$$
$$df_{AB} = (a-1) \cdot (b-1) = 4 \quad (9)$$

(10)

Calculating the value *MS* (*Mean of Square*) as a quotient of the value *SS* and the corresponding degree of freedom *df*. In conclusion, the value *F* is a calculated as the quotient of the revelant *MS* and MS_{TOT}:

$$F_A = \frac{MS_A}{MS_{TOT}} = \frac{234.6665}{25.13265} = 9.337123 \quad (11)$$

$$F_A = \frac{MS_B}{MS_{TOT}} = \frac{0.584772}{25.13265} = 0.023267 \quad (12)$$

$$F_{AB} = \frac{MS_{AB}}{MS_{TOT}} = \frac{29.46772}{25.13265} = 1.172488 \quad (13)$$

Similarly, the same procedure is performed in calculating the values F_B and F_{AB}. The calculated values are compared with F_{krit} (a tabular value for the respective degrees of freedom) and the statistical significance of each variable parameters is assessed.

If the following applies:

$$F > Fkrit \quad (14)$$

then the effect of the respective level is statistically significant.

Results and discussions

Comparing the values *F* and F_{krit}, the significance of effects of a relevant technological parameter on the surface roughness parameter *Rz* is assessed. If the relationship (14) does not apply, the corresponding value in the column *F* is denoted with the sign **x** (if so – the sign √ is used). From the acquired results mentioned above, it is clear that the signification differs for diameters of individual tools. For the instrument with a diameter of 7.0 mm, only the line denoted as *Selection* is statistically significant – and thus only the spindle speed of the tool affects the nature of the surface. For the instrument with a diameter of 5.0 mm, only the line denoted as *Columns* is considered statistically significant (table 7) – feed rate. The interaction of the factors *A*, *B* and the actual impact of speed have not been proven. In case of the latter mentioned instrument, 3.0 mm in diameter, the two factors, and the interaction between them are not statistically significant. The presumption referred to in the description of the experiment – the significance of the effect of technological parameters being changed on the surface texture will be identical – was not confirmed. The differences between the results were caused by the material itself – its inhomogeneity (diversity along the volume of the extruded profile).

Conclusions

The quality of the resulting surface is given by the material properties that are different along the extruded profile – as demonstrated by the results of the tests: tension and triax bending tests. The values of the ultimate tensile strength differ by less than 10 MPa (differences between the samples listed in table 1). Given that the examined samples were taken from the center of the profile along the axis of extrusion, it can be assumed that in the preparation of the samples from the profile edge, the differences between the values of mechanical properties to be more pronounced. Images taken by optical microscopy (fig. 1) point out to microcracks in the area of contact between the plastic matrix and reinforcement, and the cracks in wood chips. Given that it is only one technology being assessed – drilling, it can be assumed that in case of three instruments differing from each other only by their diameters (while maintaining constant spindle speeds and feed rates), the impact of input factors on the final characteristics should be the same. However, the given theory is not valid due to the fact that the material is not uniform throughout its cross-section, which caused the differences between the individual instruments with respect to the output parameter *Rz* being assessed. The applied mathematical model pointed out that in the process of assessing the statistical significance, also the homogeneity of the material plays a role (which is supported by both the tests of mechanical properties and the images of ground surfaces of the extruded profile). The model helps to fast orientation in assessing the significance of the factors for the emerging surface texture of WPC composite materials. The solution in the present paper is original and useful in both the research plane and in practice.

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