11. Kulbych, I. K., Lototska, O. I. (2013). Otsinka yakosti vidbytkiv pry tsyfrovomu drutsi. Tekhnolohiya i tekhnika drukarstva, 4, 25–39. Available at: http://nbuv.gov.ua/UJRN/Titd_2013_4_6
12. Smolarek, I. (2018). Standaryzacja procesów poligraficznych jako element ciągłego doskonalenia. Świat Druku, 5. Available at: http://www.swiatdruku.eu/Archiwum/Rok-2018/05-2018/Standaryzacja-procesow-poligraficznych-jako-element-ciaglego-doskonalenia/(language)/pol-PL
13. Buczynski, L. (1999). Special print quality problems of ink jet printers. Recent Progress in Ink Jet Technologies II, 538–544. Available at: https://www.imaging.org/site/PDFS/Papers/1999/RP-0-92/2088.pdf
14. Jang, W., Allebach, J. P. (2005). Simulation of Print Quality Defects. Journal of Imaging Science and Technology, 49 (1), 1–18. Available at: https://www.ingentaconnect.com/contentone/ist/jist/2005/00000049/00000001/art00002?crawler=true

UDC 674.061.02:674.055
DOI: 10.15587/1729-4061.2020.212484

DETERMINING THE REGIME PARAMETERS FOR THE SURFACE CLEANING OF POST-CONSUMER WOOD BY A NEEDLE MILLING TOOL

S. Gayda
Doctor of Technical Sciences, Associate Professor*
E-mail: serhiy.hayda@nltu.edu.ua
O. Kiyko
Doctor of Technical Sciences, Professor*
E-mail: orest.kiyko@nltu.edu.ua
*Department of Technology of Furniture and Wooden Products
Institute of Woodworking, Computer Technology and Design
National Forestry University of Ukraine
Henerala Chuprynky str., 103, Lviv, Ukraine, 79057

This paper addresses the identified issue of the inefficient use of post-consumer wood (PCW) in the technological wood processing due to its surface contamination. An option to resolve this issue by cleaning PCW in a mechanized manner has been proposed, specifically by using a needle milling tool and selecting the tension value and feed rate. The impact of the tension of needle milling tools before processing on the cleaning depth of the contaminated surfaces of workpieces made from the PCW has been determined. The constructed model of the contact between a needle milling tool and the contaminated PCW surface has made it possible to describe the essence of the cleaning technique involving this tool. It was found that the depth of the layer removed by the needle milling tool's wire is reduced in proportion to an increase in the distance before cutting is completed. A nomogram has been built to determine a change in the front angle depending on the needle milling tool's tension value. Knowing the front angle at a certain point of the needle touch on the contact arc enables determining the thickness of cleaning, which is important for practical application, specifically, at a tension of 4.5 mm the thickness of the removed material can equal 3.46 mm. An adequate regression model was derived, the analysis of the coefficients of which showed a significant impact of tension (+0.895) on the depth of cleaning over the feed speed (+0.256). The devised model makes it possible to forecast the thickness of the removed layer to ensure the required cleanliness of the PCW wooden. Practical recommendations on the operational modes of a needle milling machine have been formulated: the feed rate should equal 10–12 m/min, the tension – 0.5–5.0 mm, which could ensure, depending on the material's type, hardness, and the kind of PCW surface contamination, the removal of the surface layer with a thickness of 0.4–4.0 mm. A rational tension of the needle milling tool of 2.5 mm has been proposed for industrial application, which ensures the cleaning depth of contaminated surfaces within the range of 1.8–2.2 mm

Keywords: post-consumer wood, wood processing, wood science and technology, needle milling tools, wood residues, waste recycling

Received date 04.04.2020
Accepted date 16.09.2020
Published date 13.10.2020

1. Introduction

A potential resource and an underutilized base of wood raw materials, whose reserves increase in proportion to the development of the country's industry and economy in general, are the stocks of post-consumer wood (PCW). While being an additional resource of timber mass [1, 2–7], this raw material, due to the lack of technological advancements and recommendations (from collection to the manufacture of size-quality blanks and products), is not involved in processing at the furniture and woodworking enterprises.

It is a relevant task to develop highly efficient mechanical techniques to clean PCW, which would maximally take into consideration the physical-mechanical properties of recycled materials. That is why this scientific study is aimed at determining the regime parameters for the surface cleaning of post-consumer wood with a needle milling tool. This is of interest to woodworking specialists as the maximum utilization of wood waste, including cleaned PCW, under modern conditions provides manufacturers with an additional source of raw materials.

2. Literature review and problem statement

There are studies that addressed the possibility of utilizing PCW in the production of carpenter plates [6, 7], which involved PCW as it is for the inner layer of plates, as well as in the crushed form [7, 8], which indicated ways to clean the crushed PCW. However, as for the use of PCW in a massive (whole) form in wood processing, there are no developments or the problem was not sufficiently studied [6, 7, 9–13]. However, the use of wood waste, specifically PCW, as a material without additional treatment, is problematic, particularly due to various contaminations of timber. The issue is related to removing a top layer from the panel elements: paper, films, veneer, paint and varnish coatings. The task implies choosing a tool with which it would be possible to clean (polish) these coatings with different hardness [14]. Therefore, there is a problem – how do we clean up PCW? Sanding and abrasive tools cannot always be used for this purpose. Needle milling tools and wire brushes have long and successfully been used for machining metals, plastics, rubber, and other materials. These tools are extremely reliable, durable, and ensures the necessary quality of the treated surface.

Timber waste, specifically post-consumer wood, as an additional reserve of raw materials, attracts great interest of scientists to the methods and directions of its processing [1–5, 15]. Paper [1] reports a study into the burning of PCW rather than using it as a material. Works [2, 3] detail the assortment and growing number of PCW but do not specify rational ways of material use of a given raw-material additional resource. Papers [4, 5] describe the processes of timber processing after using it, as well as wood residue, but there are no specified or described processes for cleaning contaminated wood, no practical recommendations are offered. Study [15] notes a change in the characteristics of wood with age, which is typical of PCW. The issue of cleaning it from various contaminants remained unresolved.

At present, there is a series of scientific advancements by scientists regarding mainly the ways of cleaning metallic surfaces, specifically by needle milling tools or brushes. Scientific, theoretical, and practical studies [16–19] examined the impact of the processing mode parameters involving needle milling on the formation and optimization of the geometric structure of the surface of the steel blanks. The authors proposed the regime parameters for surface treatment (cutting speed, feed speed, and tension) that form the roughness characteristics for steel parts. They also constructed mathematical models that make it possible to optimize the needle milling mode parameters depending on the requirements for the roughness of workpieces' surfaces. The magnitude of a needle milling tool tension for other materials other than metal was not investigated. Paper [20] reports the dependences of roughness parameters on the structural and geometric parameters of a needle milling tool during cleaning, decorative processing, and cutting of metals. The authors suggested a mechanized process of deburring using the designed composite needle milling tools. The issue of processing wooden contaminated surfaces, having different thickness of coatings and, moreover, made from different materials, remains unresolved.

Based on the study results, it was found in [21] that metallic brushes of different designs during rotation in a contact with the workpiece create a surface relief in the form of smoothing, scratching, and cutting. The authors devised recommendations for machining metallic surfaces with brushes, which relate to reducing surface roughness, removing corrosion and paint coatings, processing hot-rolled metal, increasing the amount of forging; they found that an important characteristic of the process of machining the articles with rotating metallic brushes is the overlap factor, which depends on the parameters of the brush and processing mode. The issue is due to that the brushes as a tool cannot clean contaminated surfaces because they have lower elastic properties in contrast to needle milling tools. Papers [22, 23] report the results of studying the nature of the interaction between a needle milling tool's wires and the treated surface – contact zones, the impact of cutting modes, and the tool parameters, on process performance. It was established that of all processing parameters, tension has a greater effect on the size of the contact area of a needle milling tool than the speed of cutting. The authors did not investigate the effect of tension before treatment on the depth of cleaning, specifically wooden contaminated blanks; no nomogram was built to determine the front negative angle.

The author of work [24] resolved the issue of stiffness during the elastic contact between a needle-milling tool's micro cutters and the surface of the hardened pitch. The essence of the contact problem is to establish the interaction of two elastic bodies and the principle of distribution of the system's potential energy, in which the rigidity of structural interaction approaches a maximum. The proposed criterion of the optimality of the specific energy of deformation can be used in the study of the processes of cleaning PCW. The issue of the tension of a needle-milling tool's cutters relative to the surface of the cleaned workpiece was not solved.

It was established in [25] that the needle milling process, which is widely used in metalworking, is effective for the debarking of round timber, which makes it possible to clean logs and regulate the degree of bark removal. It was found that needle milling tools are highly durable and are capable of self-sharpening. The paper did not investigate the issue of plane cleaning, but only cylindrical, specifically logs from the bark. Study [26] devised recommendations for the use of needle milling tools for wood polishing and proposed cleaning by the needle milling tools the panel assembly units of old furniture items whose service expired. Several studies addressing the cleaning of sized-fit elements from PCW using needle milling tools are reported in [6, 7, 10–12, 26]. It was found that those studies did not resolve some issues, specifically, the authors did not build a regression model of PCW cleaning depending on the feed rate and tension for the development of mode parameters of the operation of a needle-milling machine; no practical recommendations on regime parameters for the surface cleaning of post-consumer wood by needle-milling tools were offered.

Thus, there is a problem of recycling post-consumer wood, particularly in the whole massive cleaned form. Woodworkers typically used primary wood for production and did not pay attention to the increasing amount of PCW in each country. In order to reduce the environmental burden, it is a pressing issue today to materially utilize cleaned PCW. Practical recommendations are required to apply PCW industrially. In other words, there is a concern for the woodworking sector – the absence of resource-saving and environmentally-friendly technologies for the preparation of the PCW product range, specifically at the stage of surface cleaning. All this suggests that it is advisable to conduct scientific, theoretical, and practical studies aimed at the development of regime parameters for the surface cleaning of PCW by needle milling tools in industrial production. The result would be the material utilization of PCW rather than burning this additional wood resource.

3. The aim and objectives of the study

The aim of this study is to determine the regime parameters for the surface cleaning of post-consumer wood using the needle-milling tools.

To accomplish the aim, the following tasks have been set:

– to determine the effect of the needle milling tools' tension before treatment on the cleaning depth of the contaminated surfaces of workpieces made of post-consumer wood;

– to build a regression model of PCW cleaning depending on the feed rate and tension in order to develop the operational mode parameters of a needle-milling machine;

– to offer practical recommendations regarding the regime parameters of the surface cleaning of post-consumer wood using the needle milling tools.

4. Materials and methods to study the regime parameters of the surface cleaning of post-consumer wood using the needle milling tools

4. 1. The examined materials and study methods

Our study used the woodwork and construction products whose service life expired, specifically, old window and door frames, roof wooden structural elements, plank floor. These wooden materials, with their surface contamination [10–12] with various organic and inorganic protective means, paint and varnish, paper, or film materials, were exposed to cleaning and could become measurable and high-quality blanks for woodworking industries.

Basic methods: a mathematical theory of experiment planning – to derive regression models and analyze them; mathematical modeling – to solve the optimization problems of the mathematical and regression models; mathematical statistics – to treat the results of experimental studies, specifically the Statgraphics software. The experimental and theoretical studies were conducted using a system approach, employing computers and available software.

4. 2. Simulation of the process of surface cleaning of blanks made from PCW using the needle milling tools

To simulate the surface cleaning process, a principal diagram was built for the cleaning of PCW surfaces by needle milling tools (Fig. 1).

The study's output parameter is cutting depth, t, mm. The input parameters for the study description: R_{nm} is the radius of a needle milling tool, mm; h is the tension before processing, mm; h_p is the tension during cutting, mm; d is the needle diameter, mm; l is the needle length, mm; a is the gap between the body and surface, mm; α is the rear angle (formed during processing), degrees; β is the angle of needle sharpening, 90°; θ is the front angle, degrees; $\gamma=\theta-90$ is the front angle, degrees; v_s is the feed rate, m/min.

To determine the output parameter (cutting depth), we have built an estimation scheme of the PCW surface cleaning process using a needle milling tool. Fig. 2 shows the principal simulation of surface cleaning with four pairs of needles, which, due to a different tension during cutting, have different angles of needles tilt. For a full assessment of the process of cleaning with needle milling tools, a frontal model of cleaning was constructed (Fig. 3).

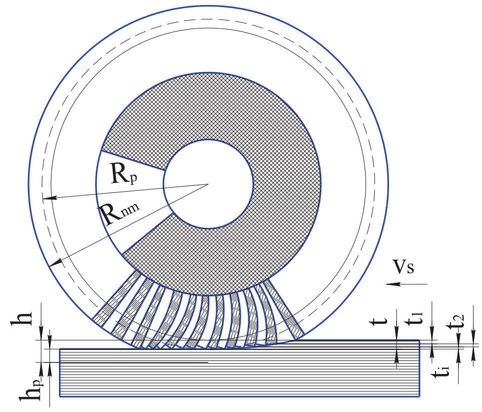

Fig. 1. Modeling the process of PCW surface cleaning by a needle milling tool

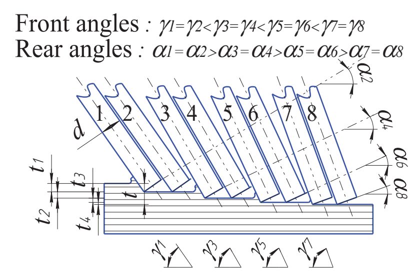

Fig. 2. Estimation scheme of the PCW cleaning process using needle milling tools

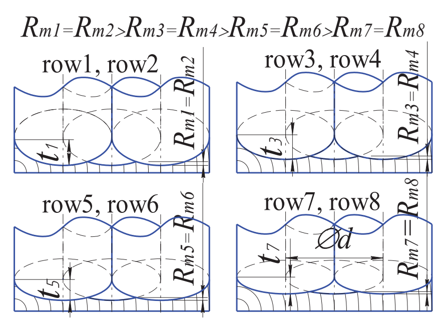

Fig. 3. Frontal diagram of the PCW needle milling process

In order to control the process of needle-milling, it is necessary to know the nature of the tool's interaction with the cleaned surface, the impact of processing modes, and tool parameters on the performance of the process and the quality of the cleaned surface. Therefore, the use of needle-milling to clean the surface, similarly to other methods of wood processing, requires the optimization of parameters of the technological operation of cleaning.

Fig. 3 shows that the highest height of profile irregularities and the depth of the layer removed by the wire of needle milling tool decreases with an increase in the distance before the end of cutting, that is, with the increase in its serial number. That is, the fourth pair of cutting elements, as shown in the principal diagram, cuts the smallest layer. This is due to that as the layer that is removed decreases, the gap between the base of the needle milling tool and the surface of the partially cleared workpiece increases. This reduces the front negative cutting angle (that is, tension, respectively) and the profile of the cutting wire of the needle milling tool in the frontal cross-section.

4. 3. The procedure of the experimental study

We have experimentally determined at the needle-milling machine (Fig. 4) the cleaning depth t at two variable factors: the feed rate v_s and tension h.

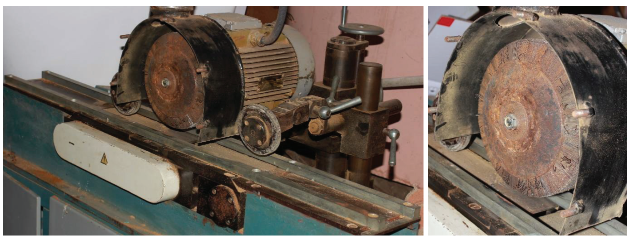

Fig. 4. Experimental installation for surface cleaning using a needle milling tool

To carry out experimental research, we selected a compositional plan with an orthogonal part at the center of the plan (B-plan of the second order). The reasons for choosing the composition plan are the following factors: the simplicity and ease of use; the possibility of a staged transition from a linear to the quadratic model.

To perform the factorial experiment aimed at determining the depth of cleaning t (output variable), two variable factors were studied: the feed rate v_s in the range of 6–18 m/min, and the tension h within 0.5–4.5 mm (Table 1).

Table 1

Experiment methodological grid

No.	Title	Measuring unit	Designation	Change interval	Factor level		
					–1	0	+1
1	Feed rate	m/min	v_s	6	6	12	18
2	Tension	mm	h	2	0.5	2.5	4.5

The feed rate is selected based on the structural characteristics of the machine and is rational for these types of operations that provide appropriate performance. The range of the working tension would ensure the complete removal of the corresponding thickness of the contaminated material layer from the PCW surface. The most likely layer of the material to be cut would be within 0.5–2.5 mm.

5. The results of studying the regime parameters of the surface cleaning of post-consumer wood using the needle milling tools

5. 1. Determining the impact of the needle milling tool tension before treatment to the depth of cleaning the contaminated surfaces of blanks made from post-consumer wood

The theoretical model of the controlled parameters of PCW cleaning is represented through geometric calculations. The total depth of cleaning t_Σ is the sum of the depth of layers that are cut by the i-th element.

The total cleaning depth t of the surface contaminated layer during PCW cleaning is recorded by the following formula:

$$t_\Sigma = t_1 + t_2 + t_3 + \ldots + t_i, \quad (1)$$

where $t_i = 0.5 \cdot d_i \cdot \sin\gamma_i = 0.5 \cdot d_i \cdot \sin\alpha_i$; d is the needle diameter, mm; α is the rear angle (formed during processing), degrees; θ is the front angle; degrees; $\gamma = \theta - 90$ is the front angle (negative for needle milling tools), ($\gamma_i = \alpha_i$) degrees.

After fitting to expression (1), the cleaning depth formula will take the following form:

$$t_\Sigma = t_1 + t_2 + t_3 + \ldots + t_i =$$

$$= 0.5 \cdot d_i \cdot (\sin\gamma_1 + \sin\gamma_2 + \sin\gamma_3 + \ldots + \sin\gamma_i). \quad (2)$$

To determine the front and rear angles of the cutting elements required for the numerical calculations of the cleaning surface depth, a scheme of cleaning blanks from PCW was built, designating the contact sectors (Fig. 5). In this case, the following properties of needle milling are manifested:

1) the presence of three sectors of the tool contact with a workpiece: the area of the preliminary needle deformation; the contact area with cutting sections and needle sliding on the cleaning surface; the zone of accelerated movement of needles after detachment from the workpiece;

2) an increase in tension leads to a decrease in the front angle θ and an increase in the negative angle γ of the cutting elements;

3) a significant impact on the size of the area of direct contact is exerted by tension, and much less – the speed of cutting.

Based on the analysis of the built model of contact between a needle milling tool and the PCW surface, we obtain several central sectors, which are separated by conditional points from 1 to 5. All angular measurements originated from central point 3. All needles located on the left of point 1 occupy a strictly radial direction. In the movement from point 1 to 2, the needles gradually bend. Point 2 denotes the beginning of the needles' touch to the cleaning surface, where the deformity increases, and the front angle θ decreases. Point 3 is on a normal to the surface, which passes through the axis of the needle milling tool. Passing the distance between points 2 and 3 by 50–70 %, the front row of needles, which is clamped by the following ones, begins the process of cleaning the PCW surface. When the tool is rotated further, the distance between the base of the needles and the surface increases. This reduces their deflection and increases the front angle, which ensures the efficiency of the cutting process. Then the needles come to the surface and slide on it at an increased speed. The accelerated movement of needles starts at point 4. When moving to point 5, all needles acquire a radial position. Thus, we obtain the central angles: $\varphi_1 - \varphi_2$ is the angle when the needles begin to deform; $\varphi_2 + \varphi_4$ is the angle when they contact the PCW surface; $\varphi_5 - \varphi_4$ is the angle when the needles are detached from the cleaned PCW surface.

Based on the results of experimental studies, a nomogram was built (Fig. 6), which determines a change in the front angle depending on the tension value of the needle milling tool, that is, based on the length of the deformed contact arc (the larger the tension, the greater the arc length). Thus, knowing the front angle at a certain point in the touch of the needle on the contact arc, one can determine, in numerical terms, the thickness of cleaning t_i.

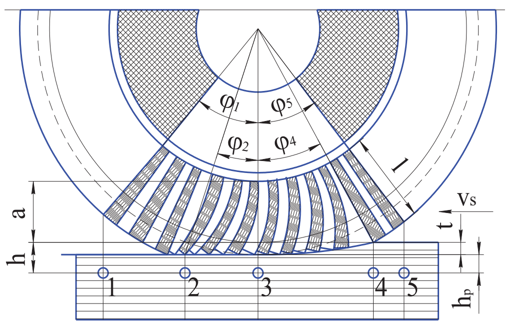

Fig. 5. The sectors of needle contact with the surface of a PCW workpiece

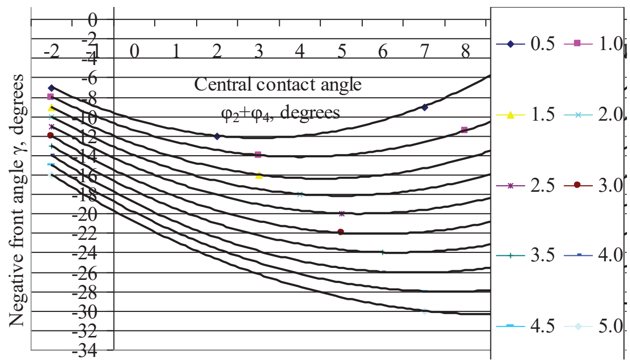

Fig. 6. Nomogram determining the front negative angle

The results of theoretical studies of the cleaning depth according to formula (2) are given in Table 2 and shown in Fig. 7.

Table 2

Data from the theoretical studies of cleaning depth

Tension h, mm	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Angle change, °	12/11	14/11	16/12	18/13	20/14	22/15	24/17	27/17	29/18	31/18
Quantity i	1	3	4	5	6	7	7	10	11	13
Depth t, mm	0.31	0.62	1.22	1.82	2.11	2.39	2.66	3.21	3.46	4.00

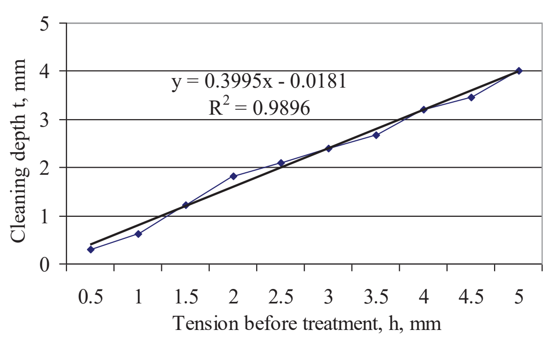

Fig. 7. Dependence of cleaning depth t on tension before the process of PCW processing

When fitting the values of angles that arise during the cutting process and depend on the tension to the theoretical model makes it possible to predict the thickness of the layer that is removed. The results of the graphical interpretation show an almost direct proportional relationship between the input and output factors.

5. 2. Results of experimental studies of the depth of cleaning the PCW blanks using the needle-milling machines

Experimental studies were conducted in accordance with the developed planning matrix (Table 3).

Table 3

The matrix of B-plan of the second order

Experiment No.		Values of input factors in the experiment			
		In natural terms		Encoded	
		v_s	h	x_1	x_2
Complete factor plan 2	1	6	0.5	–1	–1
	2	18	0.5	1	–1
	3	6	4.5	–1	1
	4	18	4.5	1	1
Star points	5	6	2.5	–1	0
	6	18	2.5	1	0
	7	12	0.5	0	–1
	8	12	4.5	0	1

Each experiment was repeated (duplicated) five times, according to the results of the statistical treatment of the search experiment.

The results of experimental studies, the average sample value, the sample variance are given in Table 4.

Table 4

Results of experimental studies, the average sample value, the sample variance

Experiment No.	Results y_{ij} of PCW cleaning depth, mm					Average value in the j-th sample	Variance in the j-th sample
	y_{1j}	y_{2j}	y_{3j}	y_{4j}	y_{5j}		
1	0.150	0.250	0.330	0.460	0.660	0.370	0.0392
2	0.130	0.200	0.360	0.470	0.590	0.350	0.0358
3	3.260	3.110	2.910	3.340	3.480	3.220	0.0480
4	2.460	2.330	2.860	3.380	3.670	2.940	0.3338
5	1.380	1.890	2.090	1.580	2.210	1.830	0.1202
6	2.150	2.030	1.700	1.630	1.290	1.760	0.1166
7	0.550	0.140	0.350	0.680	0.280	0.400	0.0464
8	4.040	3.480	3.670	3.330	4.480	3.800	0.2151

The variance check was carried out by the Cochrane's criterion. The estimated value of Cochrane's criterion is G_{est}=0.35. The tabular value of the Cochrane's criterion is G_{tab}=0.39 (N=8; f=n–1=4; q=0.05). Since G_{est}<G_{tab}, with a 95 % confidence probability, the variances of the samples are homogeneous.

The variance of reproducibility was determined from the following formula:

$$S_y^2 = \frac{\sum_{j=1}^{N} S_j^2}{N}. \quad (3)$$

The variance value of reproducibility is $S_y^2 = 0.119$.

Regression equation ratios were calculated on the basis of the procedure for their determining for the second-order B plans depending on the number of experiments N=8 and the number of variable factors k=2. Table 5 gives the results of calculations and verification of the significance of regression equation coefficients.

Table5

Results of calculations and verification of the significance of regression equation coefficients

Coef-ficient	Coef-ficient value	$t(q,f)S\{b_i\}$	Conclusion	Confidence interval limits	
				$b_i-t_{tab}S\{b_i\}$	$b_i+t_{tab}S\{b_i\}$
b_0	2.175	0.352	significant	1.823	2.527
b_1	–0.062	0.129	insignificant	–0.190	0.067
b_2	1.473	0.129	significant	1.345	1.602
b_{11}	–0.380	0.273	significant	–0.653	–0.107
b_{22}	–0.075	0.273	insignificant	–0.348	0.198
b_{12}	–0.065	0.158	insignificant	–0.223	0.093

To determine the value of adequacy variance (S^2_{ad}), the sum of squares of the difference between the experimental and estimated value of the depth of PCW cleaning in each experiment was calculated. The results of this calculation are summarized in Table 6.

Table 6

The results of calculating the sum of squares of the difference between the experimental and estimated value of the depth of PCW cleaning in each experiment

Experi-ment No.	Value		$(\bar{y}_j - y^p_j)^2$
	Experimental $\bar{y}_j$	Estimated y^p_j	
1	0.37	0.24	0.01605
2	0.35	0.25	0.01000
3	3.22	3.32	0.01000
4	2.94	3.07	0.01605
5	1.83	1.86	0.00071
6	1.76	1.73	0.00071
7	0.40	0.63	0.05138
8	3.80	3.57	0.05138
Total			0.15627

The value of adequacy variance was determined from the following formula:

$$S^2_{ad} = \frac{n}{f_{ad}} \sum_{j=1}^{N} \left(\bar{y}_j - y^2_j\right)^2, \tag{4}$$

where n is the number of duplicated observations; f_{ad} is the number of powers of the adequacy variance value $f_{ad}=N-P$; N is the number of experiments; P is the number of estimated coefficients of the regression equation; $\bar{y}_j$ is the average value of the results of the experiment in the j-th experiment; y^p_j is the estimated value of the output quantity in the j-th experiment, calculated from the regression equation.

The adequacy variance is $S^2_{ad} = 0.391$. The adequacy of the mathematical model was tested by the Fisher's F-criterion, which compared the variance of adequacy S^2_{ad} and reproducibility S^2_y. The estimated value of the Fisher's criterion was determined from the following formula:

$$F_{est} = \frac{S^2_{more}}{S^2_{less}}, \tag{5}$$

where S^2_{more} and S^2_{less} are the adequacy and reproducibility variance; the largest of them must be in the nominator and the smallest one – in the denominator.

The tabular value of the Fisher's criterion F_{tab} depends on the level of significance q, the number of degrees of freedom of the adequacy variance f_{ad} and the number of independent assessments of the reproducibility variance $f_y=N(n-1)$. If $F_{est}<F_{tab}$, the model is considered adequate and can be used to describe the object. Fisher's criterion estimated value is $F_{est}=3.27$. The Fisher's tabular value is $F_{tab}=3.32$ ($q=0.05$; $f_{more}=2$; $f_{less}=32$). Since $F_{est}<F_{tab}$, then the derived regression model with a confidence probability of 95% is adequate and can be used to describe the object of the study.

Based on the results of studying the surface cleaning using a needle milling tool according to the devised methodology in the implementation of the B-plan of the second order, we derived the regression equation for the depth of PCW cleaning, which, in the coded values of factors, takes the following form:

$$y = 2.175 - 0.062x_1 + 1.473x_2 - \\ - 0.38x_1^2 - 0.075x_2^2 - 0.065x_1x_2, \tag{6}$$

and is recorded in a natural (explicit) form as follows:

$$t = -1.3438 + 0.25654v_s + 0.89524h - \\ - 0.01055v_s^2 - 0.01875h^2 - 0.00542v_sh. \tag{7}$$

The study results in the graphic representation are shown in Fig. 8. The graphic interpretation of the implementation of the composition plan of the second order clearly demonstrates the increase in the size of the cleaned layer when the feed rate increases from 6 to 12 m/min and, quite obviously, when the tension increases – the layer is also cleaned.

The process of sample cleaning is shown in Fig. 9; the cleaned samples are demonstrated in Fig. 10.

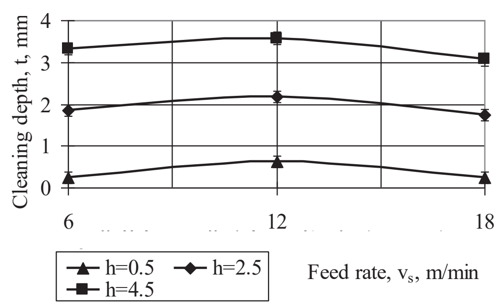

Fig. 8. Graphic dependences of the size of the removed layer on the feed rate v_s and tension value h

Fig. 9. The process of surface cleaning of PCW blanks

Fig. 10. PCW blanks after surface cleaning

6. Comparison of results and practical recommendations on the mode parameters of the surface cleaning of PCW with a needle milling tool

The comparison of the results of theoretical calculations with the data from the experiment is shown in Fig. 11. An analysis of the comparison of our results showed permissible deviations, which on average amount to 4.5 %.

The practical recommendations for the technological operation of cleaning with a needle milling tool are given in Tables 7, 8.

Thus, we have formulated the recommendations on choosing a technique for cleaning PCW with certain contamination, as well as the practical recommendations on the modes of operation of the needle-milling machine of passing type.

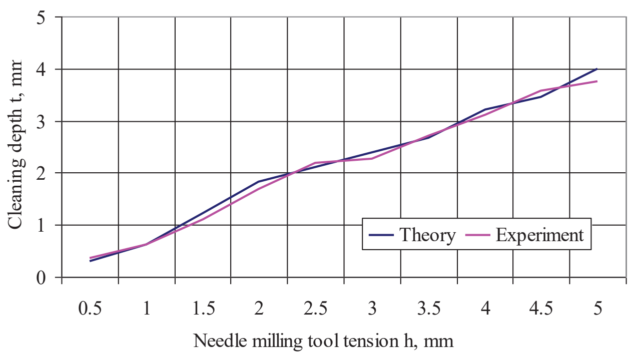

Fig. 11. Comparison of the results of the theoretical calculations of cleaning depth depending on the tension of needle milling tools with the data from the experiment

Table 7

Recommendations for the process of cleaning PCW surfaces

Needle milling tool indicator	Designation	Operation mode	
		Range	Recommendation
Needle milling tool diameter, mm	D_{nm}	150–500	200–300
Needle length, mm	l	20–160	50–160
Processing speed, rpm	v	360–1800	720–1440
Feed rate/min	v_s	6–12	10–12
Tension value, mm	h	0.1–6.0	0.5–5.0
Cutting depth, mm	t	0.05–5.0	0.4–4.0

Table 8

Rational parameters of the technological process of surface cleaning of various types of PCW with a needle-milling machine at the amount of tension h=2.5 mm

Material	Hardness HBW_m, MPa	Reserve factor K_r, HBW_{st}/HBW_m	Processing speed v, rpm	Feed rate v_s, m/min	Cutting depth t, mm
Spruce	1.3	11.52	1440	12	2.175
Fir	1.6	9.28	1080	12	2.175
Pine	2.5	6.04	720	8	2.048
Oak	3.7	4.06	540	6	1.859
Beech	3.8	3.95	540	6	1.859
Particleboard/veneer	4.1	3.67	540	6	1.859
Particleboard/PVC	3.9	3.85	540	6	1.859
PCW/varnish	2.4	6.26	720	10	2.154
PCW/paint	2.3	6.54	720	10	2.154
Steel 65G	15.0	1.00			

7. Discussion of results of studying the regime parameters of the surface cleaning of post-consumer wood using the needle milling tools

One can control the process of needle milling by selecting the cutting speed and the rate of feed, the material of the wires, their diameter, working length, density, and a tension value. In addition, there is a discrete contact with the surface during the processing involving a wire tool. According to the nature of the physical processes that occur in the area of interaction of this tool with the surface of a workpiece, the following types of processing are distinguished: finishing, finishing-strengthening, cleaning, layer-by-layer removal. Based on the analysis of the built model of contact between the needle milling tool and the PCW surface, it has become possible to understand the essence of the cleaning technique involving this tool. It was established that the depth of the layer removed by the wire of a needle milling tool decreases in proportion to an increase in the distance to the end of cutting, that is, an increase in its serial number. In other words, each subsequent cutting element cuts the smallest layer. This is due to the fact that as the layer is removed, the gap between the base of the needle milling tool and the surface of the partially cleaned workpiece increases. This reduces the front negative angle of cutting (that is, tension, accordingly) and the profile of the cutting wire of the needle milling tool in the frontal cross-section. The effective removal of a contaminated layer of a certain thickness is due to the fact that the bending of the needle cutters contributes to the formation of chambers to accumulate the removed material (chips) and its removal when the cutters leave the contact area with the surface of the workpiece. Based on the results of our experimental studies, a nomogram was built, which determines a change in the front angle depending on the value of a needle milling tool tension that is the length of the deformed contact arc. Thus, knowing the front angle at a certain point of the needle touch on the contact arc, we can determine, in numerical terms, the thickness of cleaning, specifically, when the tension is 4.5 mm, the thickness of the removed material may amount to 3.46 mm. The results of the graphic interpretation of the cleaning depth dependence on tension before processing show an almost directly proportional dependence between the input and output factors with a determination factor of 0.9896.

An adequate regression model was obtained, which, depending on the rate of feed and the working tension, makes it possible to adjust the thickness of the layer that is removed. The graphical interpretation of the implementation of the second-order plan clearly demonstrates the increase in the size of the layer, which is cut, when the feed rate increases from 6 to 12 m/min and, quite obviously, when the tension increases, the cut layer also increases. The resulting regression equation coefficients show the impact of each factor on the output parameter. The coefficient of the effect of the first factor of the feed rate was +0.25654, and the influence of the second factor, the needle milling tool tension, was +0.89524. That is, the tension significantly affects the depth of cleaning. The rational tension of a needle milling tool for industrial conditions is 2.5 mm, which provides for the depth of cutting contaminated surfaces of 1.8–2.2 mm. For the better removal of the material, it is better to saw off a contaminated surface. The models built could make it possible to predict the thickness of the layer that is removed and to manage the process of needle milling to ensure the necessary cleanliness of the PCW wooden surface. Our results of experimental studies on cleaning contaminated surfaces using the needle milling tools are due to the structural features of these tools. In the presence of a significant number of cutting elements, one can perform processing at high cutting and feed speeds.

Depending on the species, the hardness of the material, and the type of surface contamination of PCW, it was determined that to remove the contaminated layer with a thickness of 0.4–4.0 mm the feed rate should equal 10–12 m/min, and the tension value – 0.5–5.0 mm. The devised technology of PCW cleaning and the proposed mathematical model of the depth of cleaning with needle milling tools, depending on the rate of feed of blanks and the tension value of the working elements, could be used for the processes of surface cleaning under industrial conditions of woodworking. Practical features imply that it is a mechanized way of preparing PCW for material utilization. In addition, the needle milling tools are extremely reliable and durable, self-cleaned, and ensures the required quality of the treated surface. All other tools have a much smaller period of operation. Effective use of the mode parameters of the surface cleaning of PCW with needle milling tools under industrial conditions is associated with a large assortment of this resource, its sized and suitable characteristics, and the variety of contamination of surfaces: the thickness and type of a coating, the varieties and hardness of a coating, etc. All of this will require additional experimental studies. At the current stage, the results from the experimental studies on the mode parameters of the needle milling machine operation confirm the hypothesis that the method of cleaning contaminated surfaces with needle milling tools is quite promising and could provide a mechanical way of qualitative preparation of PCW for further material processing. The main issues that may arise in the process of cleaning PCW with needle milling tools are the prompt adjustment as the range of PCW varies both in size and type, as well as the degree, of contamination. This study may be advanced by establishing the rational diameter of needle milling tools, determining the density and diameter of needles in the needle milling tool, finding the optimal cutting speed.

8. Conclusions

1. A solution to the issue of PCW cleaning with a needle milling tool has been proposed. We have determined the impact of the tension of needle milling tools before treatment on the depth of cleaning of the contaminated surfaces of workpieces made from post-consumer wood. A principal scheme of modeling the process of surface cleaning with needle milling tools has been built with the representation of the needle contact sectors to the surface during processing. It was established that during needle milling, increasing the tension leads to a decrease in the front angle and an increase in the negative angle of cutting elements. A nomogram has been constructed to determine a change in the front angle depending on the tension value of a needle milling tool, that is, based on the length of the deformed contact arc (the larger the tension, the greater the length of the arc). Knowing the front angle, at a certain point of the needle touching the contact arc, we can determine, in numerical terms, the thickness of cleaning, which is important for practical application. The experimental studies were carried out at the constant processing speed of 1440 rpm and the feed rate of 12 m/min. The authenticity of the theoretical calculations involving the experiment has been justified. The theoretical indicators depended on tension – the greater the tension, the greater the number of wires in a needle milling tool that participated in the cutting process, which ultimately affected the depth of cleaning.

2. An experimental machine that employed the needle milling tools was used to perform the surface cleaning of PCW blanks. An adequate regression model has been obtained, which, depending on the rate of feed and the working tension, makes it possible to adjust the thickness of the layer that is removed. The resulting regression equation coefficients testified to the impact of each factor on the output parameter. The coefficient of the impact of the first factor, the feed rate, was +0.25654, and the influence of the second factor, the needle milling tool tension, was +0.89524. That is, the tension significantly affects the depth of cleaning. The rational tension of a needle milling tool for industrial conditions is 2.5 mm, which provides for the cutting depth of contaminated surfaces of 1.8–2.2 mm. For the better removal of the material, it is expedient to saw off a contaminated surface.

3. The practical recommendations on the modes of operation of a needle-milling machine have been formulated. Depending on the species, the hardness of the material, and the type of surface contamination of PCW, it was determined that to remove the contaminated layer with a thickness of 0.4–4.0 mm the feed rate should equal 10–12 m/min, and the tension value – 0.5–5.0 mm. The devised technology of PCW cleaning and the proposed mathematical model of the cleaning depth using the needle milling tools, depending on the rate of feed of blanks and the tension of the working elements, could be used for the processes of surface cleaning under industrial conditions of woodworking.

References

1. Cichy, W., Pawłowski, J. (2009). Combustion of solid recovered fuels made from post-consumer wood waste in a power installation of low power. Drewno, 52 (182), 25–63. Available at: http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-article-BAT8-0015-0003
2. Ratajczak, E., Szostak, A., Bidzińska, G., Leszczyszyn, E. (2018). Market in wood by-products in Poland and their flows in the wood sector. Drewno, 61 (202), 5–20. doi: http://doi.org/10.12841/wood.1644-3985.301.05
3. Ratajczak, E., Szostak, A., Bidzińska, G., Herbeć, M. (2017). Potential resources of post-consumer wood waste in Poland. Journal of Material Cycles and Waste Management, 20 (1), 402–413. doi: https://doi.org/10.1007/s10163-017-0593-5
4. Saal, U., Weimar, H., Mantau, U. (2017). Wood Processing Residues. Biorefineries, 27–41. doi: https://doi.org/10.1007/10_2016_69

5. Walkowiak, M., Cichy, W. (2010). Recykling and disposal of used wood and wood residnes. Drewno, 53 (183), 135–138. Available at: http://drewno-wood.pl/pobierz-122
6. Haida, S. V. (2011). Vzhyvana derevyna – dodatkovyi resurs syrovyny. Forestry, Forest, Paper, and Woodworking Industry, 37.1, 238–244. Available at: https://publons.com/publon/29740513/
7. Gayda, S. V. (2013). Technologies and recommendations on the utilization of post-consumer wood in woodworking industry. Forestry, Forest, Paper, and Woodworking Industry, 39.1, 48–67. Available at: https://drive.google.com/file/d/0B3NnbZD66AZ-PVlVvUmpQblZWSnc/view
8. Lykidis, C., Grigoriou, A. (2011). Quality characteristics of hydrothermally recycled particleboards using various wood recovery parameters. International Wood Products Journal, 2 (1), 38–43. doi: https://doi.org/10.1179/2042645311y.0000000002
9. Gayda, S. V. (2016). Investigation of shape stability of variously designed blockboards made of post-consumer wood. ProLigno, 12 (1), 22–31. Available at: http://www.proligno.ro/en/articles/2016/1/gayda.pdf
10. Gayda, S. V. (2014). Preparation methods for processing of post-consumer wood (PCW) needle-milling and brushing machines. Aktual'nye problemy lesnogo kompleksa, 40, 65–69. Available at: http://www.science-bsea.bgita.ru/2014/les_komp_2014/gaida_sposob.htm
11. Gayda, S. V., Kiyko, O. A. (2013). Tehnologiya ochistki vtorichno ispol'zuemoy drevesiny iglofrezernymi stankami. Aktual'nye problemy i perspektivy razvitiya lesopromyshlennogo kompleksa: materialy II mezhdunar. nauch.-tehnich. konf. Kostroma: Izd-vo KGTU, 36–39. Available at: https://www.elibrary.ru/item.asp?id=21734294
12. Gayda, S. (2016). Technological approaches to cleaning of surface of post-consumer wood (PCW) of needle-milling tools. Visnyk Kharkivskoho natsionalnoho tekhnichnoho universytetu silskoho hospodarstva imeni Petra Vasylenka, 178, 3–11. Available at: http://nbuv.gov.ua/UJRN/Vkhdtusg_2016_178_3
13. Hayda, S., Kiyko, O. (2018). Shape stability as a quality criterion for PcW-made blockboards. Proceedings of the Forestry Academy of Sciences of Ukraine, 17, 185–192. doi: https://doi.org/10.15421/411834
14. Lykidis, C., Nikolakakos, M., Sakellariou, E., Birbilis, D. (2015). Assessment of a modification to the Brinell method for determining solid wood hardness. Materials and Structures, 49 (3), 961–967. doi: https://doi.org/10.1617/s11527-015-0551-4
15. Lachowicz, H., Wróblewska, H., Wojtan, R., Sajdak, M. (2019). The effect of tree age on the chemical composition of the wood of silver birch (Betula pendula Roth.) in Poland. Wood Science and Technology, 53 (5), 1135–1155. doi: https://doi.org/10.1007/s00226-019-01121-z
16. Barshay, I. L., Fel'dshteyn, E. E., Birich, A. V., Goncharov, S. P. (2009). Modelirovanie formirovaniya kachestva poverhnosti zagotovok iz chugunov pri iglofrezerovanii. Vestnik Belorusskogo natsional'nogo tehnicheskogo universiteta, 5, 31–37. Available at: https://rep.bntu.by/bitstream/handle/data/2340/31-37.pdf?sequence=1&isAllowed=y
17. SHeleg, V. K., Fel'dshteyn, E. E., Barshay, I. L. (2009). Formirovanie kachestva poverhnosti i ekspluatatsionnyh harakteristik detaley pri iglofrezerovanii i kombinirovannoy obrabotke iglofrezirovaniem i poverhnostnym plasticheskim deformirovaniem. Minsk: BNTU, 231.
18. Barshay, I. L., Glubokiy, A. S. (2013). Modelirovanie i optimizatsiya formirovaniya geometricheskoy struktury poverhnosti detaley iz stali pri iglofrezerovanii. Trudy BGTU, 2, 174–176. Available at: https://elib.belstu.by/bitstream/123456789/2804/1/55.pdf
19. Barshay, I. L., Fel'dshteyn, E. E., Goncharov, S. P. (2007). Formirovanie topografii poverhnosti detaley iz stali 12HN3A pri iglofrezerovanii. Vestnik BNTU, 4, 9–15. Available at: https://cyberleninka.ru/article/n/formirovanie-topografii-poverhnosti-detaley-iz-stali-12hn3a-pri-iglofrezerovanii/viewer
20. Kryazhev, Yu. A., Kryazhev, A. Yu., Ognevenko, E. S. (2012). Povyshenie kachestva obrabatyvaemoy poverhnosti pri iglofrezerovanii na osnove nauchno-teoreticheskih i prakticheskih issledovaniy protsessa rezaniya. Polzunovskiy vestnik, 1/1, 168–172. Available at: http://elib.altstu.ru/journals/Files/pv2012_01_1/pdf/168krajev.pdf
21. Evdokimov, V. D., Klimenko, L. P., Evdokimova, A. N. (2005). Rekomendatsii po obrabotke poverhnostey shchetkami. Tehnologiya uprochneniya mashinostroitel'nyh materialov. Odessa-Nikolaev: Izd-vo NGGU im. Petra Mogily, 268–270. Available at: http://lib.chdu.edu.ua/pdf/monograf/2/57.pdf
22. Tumash, A. M. (2011). Study of the needle-cutter contact zone with the machined surface. Vestnik Irkutskogo gosudarstvennogo tehnicheskogo universiteta, 6 (53), 13–16. Available at: https://cyberleninka.ru/article/n/issledovanie-zony-kontakta-iglofrezy-s-obrabatyvaemoy-poverhnostyu/viewer
23. Tumash, A. M., Korzun, N. L. (2015). One of methods to investigate needle cutting. Izvestiya vuzov. Investitsii. Stroitel'stvo. Nedvizhimost', 3 (14), 93–102. Available at: https://cyberleninka.ru/article/n/odin-iz-metodov-issledovaniy-iglofrezerovaniya/viewer
24. Milyanych, A. R. (2014). The Determination of the Maximum Stiffness in an Elastic Contact between the Elements of a Needle Milling Cutter and the Surface of a Congealed Pitch. Naukovyi visnyk NLTU Ukrainy, 24.4, 358–365. Available at: https://nv.nltu.edu.ua/Archive/2014/24_4/358_Mil.pdf
25. Zharkov, N. I., Gil', V. I. (2013). Primenenie iglofrezernogo instrumenta dlya okorki kruglyh lesomaterialov. Trudy BGTU, 2, 234–235. Available at: https://e.lanbook.com/reader/journalArticle/289942/#1
26. Maksymiv, V. M., Kiyko, O. A., Kryshtapovych, V. I., Matsyshyn, Ya. V. (2006). Repeated unseal shield details old frame corps furniture. Naukovyi visnyk NLTU Ukrainy, 16.7, 140–143. Available at: https://nv.nltu.edu.ua/Archive/2006/16_7/140_Maksymiw_16_7.pdf