Dry Grinding of Waste Wood Fiberboard: Theoretical and Practical Aspects Affecting the Resulting Fiber Quality

Venera Matygulina,[a,*] Natalya Chistova,[a,b] Aleksandr Vititnev,[a] and Roman Chistov [a]

This paper presents the results of research on the treatment of secondary wood fibre semi-finished materials using a dry-grinding-type rotary cutting mill and the possibility of their use in finished products for various purposes. The physical phenomena, processes, and regularities of the treatment of secondary wood fibre materials in dry processing conditions were determined and evaluated. The influence of grinding plant design parameters on wood fibre quality indices was evaluated. Mechanical effects on wood fibre waste of face-cross cutting (cutting, crumpling, collapsing, and breaking) and the dry grinding environment (breaking, collision, defibering, and fibrillation) was studied. These phenomena contribute to the formation of external and internal fibrillation of secondary wood fibre and an increase in the specific surface area. This is achieved in the absence of high temperatures and pressure, in the absence of chemical additives, and without the application of water and vapour. The effectiveness of secondary wood fibre semi-finished material treatment was demonstrated under dry processing conditions, thus confirming the environmental and economic feasibility of this method.

Keywords: Wood fibre wastes; Grinding; Defibration; Fibrillation; Dry grinding environment; Semi-finished wood fibre materials

*Contact information: a: Reshetnev Siberian State University of Science and Technology 31, Krasnoyarskii Rabochii Prospect, Krasnoyarsk 660000 Russian Federation; b: Krasnoyarsk Railway Transport Institute, Branch of Irkutsk State Transport University, 2g, Novaya Zarya Street, Krasnoyarsk 660028 Russian Federation; *Corresponding author: caress-lsib@rambler.ru*

INTRODUCTION

A resource-saving plan fully corresponds to the state policy and the main areas of the 2030 Strategy for the Development of the Timber Industry of the Russian Federation (Ministry of Industry and Trade of Russia 2018). In addition, numerous studies conducted by scientists to find resource-saving solutions and improve the quality of finished products indicate that this field of science is of great importance (Ackermann *et al.* 2000; Matygulina 2007; Chistova 2010; Morozov 2016; Vititnev 2019).

The timber industry has always occupied one of the leading positions among the industrial sectors of the Russian Federation. However, as of today, the share of this industry in the Russian economy has significantly decreased. Having more than 20% of all global timber resources within its borders, Russia occupies only 2.3% of the world's total timber production. Additionally, only 20% of Russia's harvested wood is used for advanced wood processing. The high efficiency of the timber industries of such countries as the USA, Germany, China, Canada, and Finland, is explained by their focus on advanced wood processing (Wu 2016; Khider and Hubbe 2018; Laleicke 2018; Chen *et al.* 2019) and on the use of secondary wood fibre waste to produce competitive products with high performance properties (Ackermann *et al.* 2000; Nicewicz and Leszek 2010; White 2011; Wan *et al*. 2014; Ihnát *et al*. 2017).

The wood-panel industry mainly uses softwoods, hardwoods, cut woods, and one-year-old stems as raw materials. Sawmill (slabs, racks, and sawn ends) and plywood (pencils and veneer laths) industry waste, felling waste (branches and boughs), and shavings are also used as secondary wood raw materials. Scientists from different countries are currently considering the use of alternative raw materials derived from agricultural and forest products due to their low cost (Bektas *et al*. 2005; Hiziroglu *et al*. 2008; Mancera *et al*. 2012; Hazrati-Behnagh *et al*. 2016; Wu 2016; Theng *et al*. 2017; Şahin 2020; Yano *et al*. 2020).

At that, large amounts of wood-fibre-containing waste products are generated annually. These include fibreboard production waste (slabby scrapings), waste paper, paper industry waste, and composite material waste from construction works and furniture. Many authors (Chistova 2010; Zamagni 2012; Wan *et al*. 2014; Morozov *et al.* 2015; Morozov 2016; Ihnát *et al*. 2017; Moezzipour *et al.* 2017) have considered the methods for recycling these types of wastes and the possibility of returning recycled products to core production lines.

Grinding is one of the most important operations in the production of materials containing wood fibre semi-finished products. Along with other operations, grinding has a decisive effect on the characteristics of finished products. Depending on the wood fibre treatment method, different types of knife and knifeless equipment are currently used primarily to crush wood fibre materials and give certain properties to wood fibre pulp (Smith 1922; Alashkevich 1980; Goncharov 1990; Chistova 2010; Solikhin *et al.* 2017). During grinding, wood fibres are known to break down in both cross-fibre (shortening) and longitudinal (fibre splitting and fibrillation) directions (Leonovich 2003; Li *et al.* 2011; Kozhukhov 2015; Ferritsius *et al.* 2018; Gorazdova *et al.* 2018). The authors (Goncharov 1990; McDonald *et al.* 2014; Gorazdova *et al.* 2018; Vititnev 2019) note that the most effective and preferable method is axial wood fibre breaking, which makes it possible to maintain their length and to increase flexibility and elasticity, thereby ensuring good fibre bonding in finished products. Improved fibre quality characteristics and an increased amount of fibres with high board-forming properties in total wood fibre pulp ensure good inter-fibre bonds, thereby improving the strength properties of finished products (Shi 2007; Chistova 2010; Zyryanov 2012).

When heat-treated at high temperatures and pressures, wood fibre waste takes the form of the so-called ‘inactivated’ fibres. When reprocessed in high-speed cutting mills, these fibres are unable to re-form strong inter-fibre bonds in the resulting finished products due to the so-called ‘irreversible hornification’ (Chistova 2010; Morozov *et al.* 2015).

The current authors’ previous analysis of dimensional and qualitative characteristics of wood fibre waste processed in a hydrodynamic environment (Matygulina *et al.* 2021) shows that the fibres have widespread signs of hornification. For instance, the grinding quality fractional indicator significantly decreases and fibre fibrillation is almost completely absent. Such fibres cannot form cohesive and adhesive bonds in finished products. It has been established that if the use of knife grinding machines is fully justified for the treatment of initial fibrous raw materials; then, in the current authors’ opinion, the use of these machines is impractical in the treatment of secondary wood fibre semi-finished products. Because previously processed wood fibres are repeatedly subjected to additional cutting in the cutting machines, the possibility of using secondary raw materials fully is excluded.

In the course of the study, the authors considered various types of grinding equipment: disk crusher, conical mill, pulper (using water and steam), and dry grinding machine. All other conditions were equal when evaluating the efficiency of the preparation methods. A high-speed disc crusher (a disk refiner) grinds material between the rotor cutters and the stator grinding tool. During the grinding process in such disk crushers, the initial woodfibre suspension is subject to compression and friction forces. A conical mill grinds a low concentration of plant fibre as it passes through the rotor and stator cutters due to hydraulic pressure and an increasing centrifugal force created by an increase in the diameter of a grinding compartment. Due to the high circumferential speeds of the grinding organs of these machines and excessive pressure, the wood fibers are subjected to strong chopping effects and crushing. In a semi-industrial pulper with combined fibre processing (cutting and non-cutting grinding), the separation of secondary raw materials into fibers is carried out due to intense vortex movements of the fibrous suspension (Chistova 2010; Zyryanov 2012; Matygulina *et al.* 2021).

Secondary wood fiber prepared in a dry grinding environment can be used in the production of thermal insulation boards, hard-to-burn plates, as a filler in building materials. For this purpose, it is necessary to prepare well-separated wood fibers with signs of external and internal fibrillation. This helps to increase the specific surface area of the wood carpet as a whole and bond formation in the plate.

This work explores the influence of the technological and design parameters of dry-grinding-type grinding machines on the quality indices of wood fibre, and describes physical phenomena and regularities of the treatment of secondary semi-finished products in a dry grinding environment.

EXPERIMENTAL

Materials

In the experiments, the authors used off-spec composite board products as raw materials (wet-process fibreboards and medium-density fibreboards (MDF)) not meeting Interstate Standard No. 4598 (2018) and EN 622-5 (2009) requirements, as well as their waste from panel sizing machines.

Wet-process fibreboards were obtained without using bonding material. During the MDF production, carbamide-formaldehyde resin (KF–MT–15, Himtech, Moscow, Russian Federation), sulfuric acid (Angarsk Nitrogen-tuk Plant, Angarsk, Russian Federation), mineral oil emulsion (Yaroslavl Plant of Paraffin Products, Yaroslavl, Russian Federation), ammonium chloride (Chempack, Moscow, Russian Federation), and carbamide (grade A, URALCHEM, Perm, Russian Federation) were added to the fibres. Molding compound composition for fibreboard production present in in the works (Matygulina *et al.* 2021).

Methods

The studies were facilitated by the laboratory of the Department of Machines and Devices of Industrial Technologies, Reshetnev Siberian State University of Science and Technology, using a semi-industrial grinding plant (a MR-4 rotary cutting mill, Reshetnev Siberian State University of Science and Technology, Krasnoyarsk, Russian Federation) with open-air grinding. The general view of the plant is presented in Fig. 1.

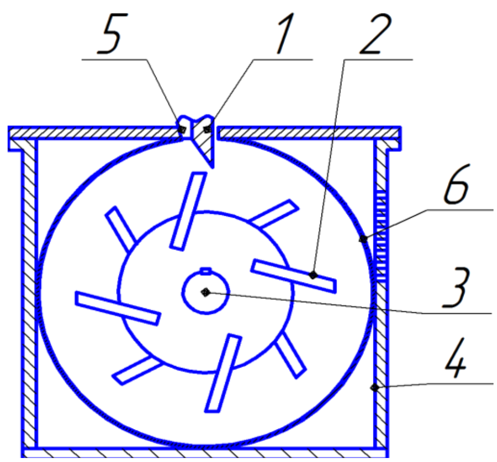

Fig. 1. General appearance of the MR-4 laboratory rotary cutting mill (1 - stator cutter (cutting anvil); 2 - rotor cutters; 3 - shaft; 4 - machine housing; 5 - booting device; and 6 – separator)

This grinding plant consisted of a housing (4) and a shaft (3) with rotor cutters (2) attached thereto. A stator cutter (1) equipped with two bevel angles was attached to the housing side covers using adjusting holding devices. Inside the housing was a separator (6) for defibering secondary wood fibres after grinding and for grinding time regulation. The separator was made in the form of a perforated metal mesh and acted as a sorting device for ground wood fibres by fractions. It also regulated the time that the fibres were kept in the grinding chamber. The grinding part was driven by a three-phase electric motor (V-belt transmission). This grinding machine could be operated in both continuous and periodic modes. The main dimensions of the MR-4 rotary cutting mill, as well as the technical characteristics, are presented in the works (Chistova *et al.* 2018a, 2018b; Matygulina *et al.* 2021).

Initial raw materials (patches and longitudinal strips of fibreboards) were fed into the machine's working chamber through a loading device to fall into the space between the rotor and stator cutters. Each protruding cutter cut a strip from the board equal in its width to the set gap between the cutter and the cutting anvil. Thereafter, this cut layer entered the working area between the rotor and the separator, where the layers were broken, attrited, and fibrillated along the fibres.

To assess the quality of the wood fibres produced in this grinding plant, the authors considered the grinding quality fractional indicator, the fibre-length-to-diameter ratio, and the specific fibre surface area.

The grinding quality fractional indicator expressed in grams shows how much the initial mass would weigh if it consisted of the same quantity of fibres of a finer fraction. This indicator was determined using a FVG-2 fractionator (Consys, St. Petersburg, Russian Federation) based on the fractionation process, *i.e.*, fibre separation by size (sieves with hole diameters of 1.0, 0.63, 0.4, 0.315, 0.2, and 0.16 mm). After fractionation, the fibres from each sieve were weighed separately and the weight of each fraction was expressed as a percentage of the total weighted sample. The fractional indicator was determined according to Eq. 1,

$$Fr = \frac{m_g}{m_n} \cdot 100 \tag{1}$$

where m_g is the group fibre mass (g), and m_n is the total sample mass (g).

Thus, the higher the value of this indicator, the higher the mass content of average and fine fractions in the wood fibre pulp.

The fibre-length-to-diameter ratio is one of the most important indicators in fibrous semi-products. It characterises the intensity of changes in the geometric dimensions of wood fibres in the longitudinal and crosswise directions, thereby determining to a greater extent their specific surface and flexibility. The average fibre length (L_a) and the average diameter (D_a) were determined according to Eqs. 2 and 3,

$$L_a = \frac{\sum l}{n} \quad (2)$$

where $\sum l$ is the total fibre length (mm), and n is the fibre number (pcs).

$$D_a = \frac{\sum d}{n} \quad (3)$$

In Eq. 3, Σd is the total fibre diameter (mm).

The specific fibre surface area, S, is an indicator that characterises the fibre bonding process. To determine this surface area, the mean length and mean diameters of fibres from each sieve were determined per fraction. For this, a curvimeter (Zlatoust Watch Factory, Zlatoust, Russian Federation) and a LV–34 digital microscope (Research and Production Company Nauchpribor, Moscow, Russian Federation) with a dividing ruler and with 100- to 1500-times maximum magnification were used. The fibres were then determined and sorted according to their fractions. The obtained mean length and mean diameter were used to calculate S and was determined according to Eq. 4,

$$S = \frac{4}{\rho}\left(\frac{1}{2L_a} + \frac{1}{D_a}\right) \cdot 10^4 \quad (4)$$

where ρ is the specific fibre weight (g/cm^3). Microscopic images were shot using a HITACHI microscope TM4000Plus (Westford, MA, USA).

To assess the influence of technological and design parameters of the MR-4 grinding machine on the quality indicators of wood fibre, the authors planned and implemented a two-factor experiment according to the second-order B-plan. The experimental results were processed in the STATISTICA-6 software package (Dell Technologies, version 6.1, Round Rock, TX, USA) using the Quasi-Newton method (Borovikov and Borovikov 1998; Pizhurin and Pizhurin 2005).

The results of theoretical and experimental studies have shown that the greatest influence on the process under study under the selected grinding conditions is exerted by such factors as the gap between the rotor and stator knives and the angle of the stator knife meeting with raw materials. The quality of the prepared secondary wood fiber is less affected by factors of mass temperature, the mass fraction of hardwoods in the mass, and the rotor speed. Thus the input factors of this experiment were as follows: the gap between the rotor and stator cutters z_{WPF} and z_{DPF} (where z_{WPF} is the gap set during wet-process fibreboard grinding, and z_{DPF} is the gap set during MDF waste grinding) and the angle of the stator cutter contact with raw materials (ε_{WPF} and ε_{DPF}). Furthermore, the article used the *WPF* and *DPF* indicators to indicate the types of fibreboards (wet process or dry process, respectively). Table 1 shows the input parameters of the experiment and the intervals of their variation.

Table 1. Experiment Input Parameters, Variation Levels, and Intervals of Factors Under Study

Parameter	Designation		Variation Interval	Variation Level		
	Natural	Normalised		-1	0	+1
Input Parameters (Controllable Factors)						
Wet-process Fibreboard						
Gap between rotor and stator cutters (mm)	z_{WPF}	X_1	3	3	6	9
Angle of stator cutter contact with raw material (deg)	ε_{WPF}	X_2	45	135	180	225
Dry Process MDF						
Gap between rotor and stator cutters (mm)	z_{DPF}	X_3	3	2	5	8
Angle of stator cutter contact with raw material (deg)	ε_{DPF}	X_4	45	135	180	225

During the two-factor experiment, after grinding wood fibre waste with the specified technological and design parameters, indicators characterising the dimensional-qualitative characteristics of wood fibres were evaluated as output (controllable) experimental parameters: grinding quality fractional indicator Fr_{WPF} and Fr_{DPF} (g), fibre-length-to-diameter ratio L/D_{WPF} and L/D_{DPF}, and specific fibre surface area S_{WPF} and S_{DPF} (cm^2/g).

The experiment was performed in the following sequence: at certain levels (specified in Table 1), the values of the gap between the cutter and the cutting anvil were recorded, while the values of the contact angle were changed by adjusting the cutting anvil. Thereafter, the angle of the cutting anvil contact with the raw material was recorded and the gap value varied. The wood fibre quality was then assessed.

RESULTS AND DISCUSSION

Wood fibre semi-products include wood fibres of large, medium, and small fractions, as well as fines in the form of fibrilplasm and mehlstoff. Table 2 shows the morphological characteristics of various fibre fractions included in the composition of wood fibre semi-finished materials during fibreboard production (Laskeev 1967; Liptsev 1982).

Table 2. Morphological Characteristics of Various Wood Fibre Fractions

Indicator	Fibre						
	Large	Medium	Small	Fines			
				Fibrilplasm		Mehlstoff	
				A	B	A	B
Length (*L*) (mm)	More than 4	4 to 1.5	1.5 to 0.2	0.3 to 0.2	0.09 to 0.04	From 0.04	0.2 to 0.15
Diameter (*D*) (mm)	More than 0.5	0.1 to 0.05	0.05 to 0.02	From 0.003		0.02 to 0.01	0.01 to 0.003
L/D	10 to 20	35 to 50	10 to 15	65 to 100	15 to 30	10 to 15	35 to 55

Through analysing the values specified in Table 2, it can be noted that large fibres have a large diameter and length. They act as reinforcing elements in the structure of board frames. Medium fibres, Group A fibrilplasm, and Group B mehlstoff have a fibre-length-to-diameter ratio that is several times higher than that of other fractions. Such fibres have a large specific surface area, and are therefore capable of forming cohesive bonds and improving the structure of boards. Fine fibres, Group B fibrilplasm, and Group A mehlstoff have a small specific surface area, and act as a filler, increasing the sheet density to a certain extent (Chistova 2010; Zyryanov 2012; Heinemann *et al.* 2016; Saharinen *et al.* 2016).

To show the bonds between different fibre fractions, Fig. 2 presents a board structure reference chart (Chistova 2010; Morozov 2016).

During the treatment of wood fibre waste in the machine under study, due its design features, there was an increase in Group A fibrilplasm and Group B mehlstoff fibres and a decrease in Group B fibrilplasm and Group A mehlstoff fines. The percentage of coarse fibres decreased (7 to 10%), the quantity of medium and small fractions increased (15 to 20%) in the total amount of pulp. This improves the board-forming properties of wood fibres.

Figure 3 shows wood fibres treated in an dry grinding environment using the MR-4 rotary cutting machine.

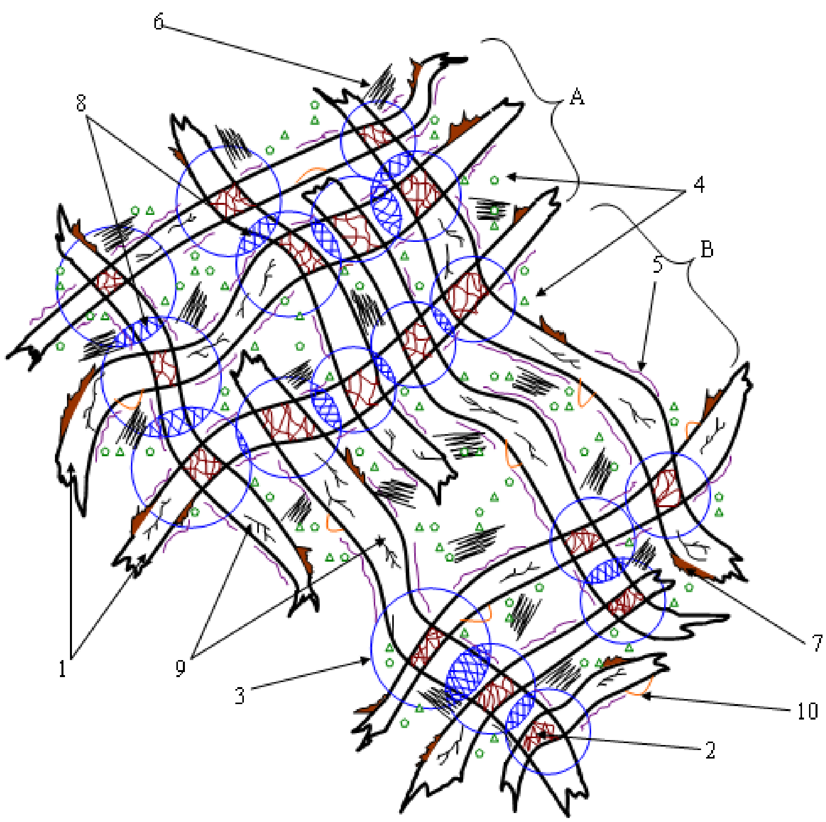

Fig. 2. Board structure reference chart (A – intergrowth unit; B – area between intergrowth units; 1 – reinforcing wood fibres; 2 – formation of hydrogen bonds and Van der Waals forces; 3 – adhesion bonds; 4 – vapour-air mixture; 5 – water-colloidal films; 6 – finely dispersed fraction; 7 – external fibrillation; 8 – cohesive bonds; 9 – microcracks; and 10 – nonfibrous component)

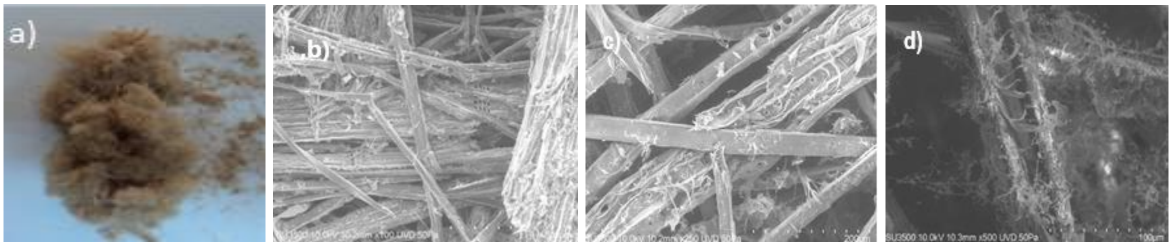

Fig. 3. Secondary wood fibres treated in an dry grinding environment using the MR-4 rotary cutting machine

During the treatment, shooting were taken to assess the processes occurring in the grinding chamber during the dry defibering of secondary wood fibres. This allowed simulating the processes and phenomena taking place in the grinding chamber during the defibering of wood fibres as homogeneous rigid polymers. Based on the research results, the treatment of woody raw material waste in the grinding machine operating according to the dry grinding method can be nominally divided into two zones: *I* – mechanical effects on wood fibre wastes and their separation by cutting, crumpling, and flattening between the rotor and stator cutters; *II* – defibering, crumpling, breaking and fibrillation of secondary wood fibres in the gap between the rotor cutters and the separator surface, accompanied by dry grinding processes. Figure 6 shows a mechanism of dividing patches into fibre bundles and individual fibres between the rotor and stator cutters.

The working element of the grinding machine represents a solid axle with rotor cutters fastened and arranged in a chequer-wise order. When the axle rotates, a working line (an outline) of the cylinder is formed, along which the grinding process takes place in the *I* zone (cutting process). Wood fibre waste in the *I* grinding zone was treated using the face-cross cutting principle (Fig. 4). The machine cutters (1) protruding above the cylinder outline surface (2) by the quantity *h* along the radius *R* rotated at a constant angular velocity *ω*. Wastes to be ground (4) were supplied at an angle of a_x to the horizontal plane that passes through the rotation centre *O* and the point *a* of the rotor cutter contact with wood fibre waste.

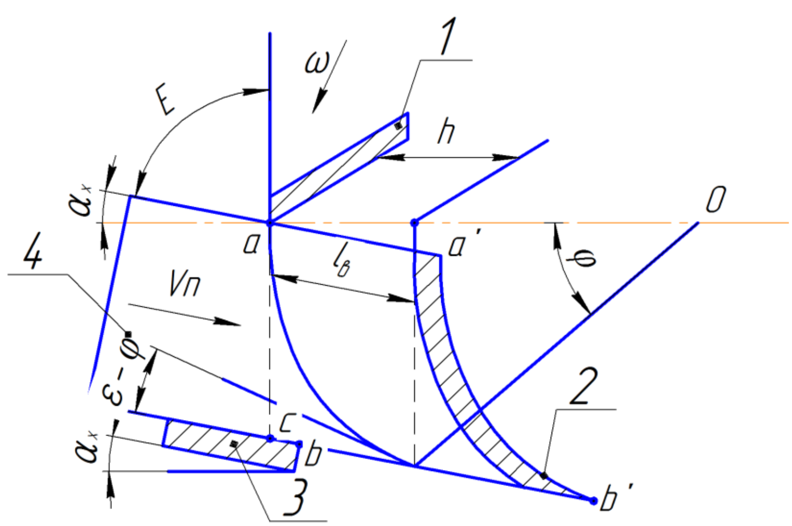

Fig. 4. Patch separation mechanism (*ε-φ*) is the fibre cutting angle (deg)

Let it be supposed that during cutting, lumpy wood fibre wastes rest against the stator cutter (3) and have a feed velocity $V_P = 0$. The cutter would then move in the board (patch) trimming along the arc *ab* formed by the rotor cutter edge with the rotation radius *R*. The next rotor cutter would approach the patch moving along the loading device by the quantity *aa'* and the face cut would be *a'b'*. When the rotor cutter enters wood fibre wastes (patches or longitudinal strips), the length of the secondary wood fibre bundle separated in the direction would be $l_v = h / cos\alpha_x$. Upon further movement of the rotor cutter along the outline, the angle of the cutter contact with raw materials ε would gradually decrease by the quantity ωt. The departure angle of wood fibre waste, initially equal to α_x, on the contrary, would gradually increase by the quantity ωt. Secondary wood fibres obtained in the MR-4 grinding plant, the variable length of which would be $l_v = h / cos(\alpha_x + \omega t)$, would have a variable cut angle and would be non-uniform in size. With the rotation of the stator cutter at an angle φ, the contact angle at point *b* would be equal to $\varepsilon - \varphi$, and the fibre cut angle would increase to $\alpha_x + \varphi$. Therefore, the smallest length of secondary wood fibres would be obtained at the patch or longitudinal strips inlet of the rotor cutter, and the largest one – at the outlet. Under real conditions, the grinding machine performs a continuous gravity feed of raw materials at a specific linear velocity V_P of the patch onto wood fibres in the gap between the rotor and stator cutters.

At that, every circumferential displacement of the rotor cutter along the patch face is compatible with its specific linear displacement. After time *t* from the reference point, the position of the rotor cutter edge point is determined by parametric equations: $x = V_P t$; $y = R \sin \omega t$.

From the current authors' point of view, it is the rotor cutter displacement along the patch face and the different length of a cutter separated in the direction of fibres at the beginning and end of cutting-in that contribute to the dimensional parameters of various fractions of secondary wood fibres along the length. Thus, by adjusting (changing and setting) the gap between the rotor and stator cutters and the inclination angle of the stator cutter, it is possible to ensure the predominance of a particular wood fibre fraction and affect the specific surface area of secondary wood fibres that ensures bonding in finished products.

Secondary wood fibres with a specified length l_v that corresponds to the fibre-length-to-diameter ratio can be obtained using the MR-4 grinding plant, but only with a gravity feed of raw materials that takes place synchronously with the rotor rotation. In this case, it is important that this feed to the working area be carried out tangentially to the machine housing. It is important to select a feed velocity V_P such that wood fibre waste would be able to move from point *a* to point *a'* along the fibre length l_v in time $t = l_v / V_P$. During the same period of time, the cutter must move from point *a* to point *b* at velocity V_p, with $t = ab / V_p$. In that case, the angle of the cutting anvil contact with raw material ε would remain constant during the grinding process. The trajectory of the cutter movement in the patch would not be an arc, but a straight line *ac* that would take the position *a'b* after time *t*. Thus, certain kinematic, geometric, and other relations must be observed in grinding equipment to ensure stable defibering and obtaining length-specific secondary wood fibres.

When the rotor cutter leaves wood fibre waste at point *b*, the next cutter must simultaneously approach point *a*. If the rotor cutter arrives to point *a* late, and the patch thickness exceeds the gap between the stator and rotor cutters, the length of secondary wood fibres cut would increase; if the rotor cutter arrives early, it would decrease. The length of the arc *ab* equal to the distance between the rotor cutters is determined by the number of rotor cutters *k* and the cutting circumference $ab = 2\pi R / k$. The linear cutting velocity V_p is determined by the circumferential velocity $\omega = \pi n / 30$ and the radius of the rotor cutter edge movement. Thus, the main technological factors of this type of grinding having the greatest influence on the defibering of wood fibre waste would be the gap between the rotor and stator cutters and the angle of the stator cutter contact with the raw material. As a cut-off patch element advances between the rotor and stator cutters, the lump element is divided into wood fibre bundles (along the fibres) and single wood fibres that then entered the *II* grinding zone. Fibres in the *II* grinding zone move in accordance with the laws of aerodynamics.

To explain and assess the treatment of secondary wood fibres in the *II* zone of the machine grinding chamber, the authors considered theoretical aspects of the movement of a one-dimensional air flow and a flow around a secondary wood fibre body with an incoming flow, conditionally accepting the movement of the wood fibres as rigid crystalline polymers.

Wood fibre particles of different granulometric composition, different weight, volume, trajectory, and velocity flew out from the gap between the rotor and stator cutters. However, it is not possible to describe and evaluate the movement of each wood fibre bundle or single fibres. Therefore, the wood fibre material under treatment in the grinding chamber was nominally divided into two main size groups: bundles and large wood fibres of more than 1 mm and small wood fibres of less than 1 mm. In the treatment of crystalline polymers in an dry grinding environment, it is possible to form a variety of supermolecular structures: fibrils, spherolites, monocrystals, *etc.* (Mandelkern 1964).

Figure 5 shows secondary wood fibre movement vectors as polymers in a dry grinding environment (bundles and large wood fibres of more than 1 mm).

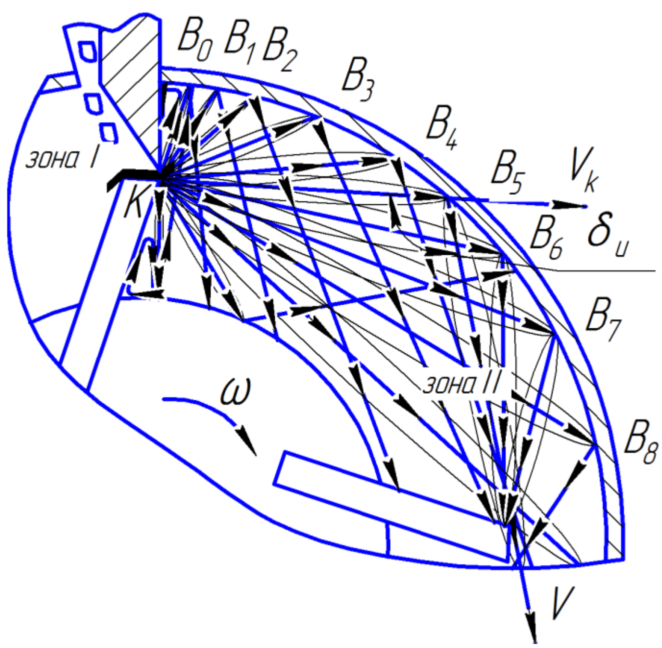

Fig. 5. Movement vectors of secondary wood fibres as rigid polymers in an dry processing conditions (Zone I – separation of secondary wood fibres due to cutting forces between the rotor and stator cutters; Zone II – defibering, crumpling, breaking, and fibrillation of secondary wood fibres in the space between the rotor cutters and the separator surface; ω is the rotor rotation direction; K is the wood fibre contact point; B_1, B_2, and B_n are the points of wood fibre collision with the separator surface; KV_k is the vector of the most probable average direction of wood fibre flight; and δ_u is the secondary wood fibre reflection angle (°)

Such structures considerably affect the properties of rigid polymeric materials, including wood fibres, which transform from a vitreous state into a highly elastic state at low temperature (indoor temperature). This ensures the further formation of fibrils on fibres with hornification signs. Wood fibres with hornification signs consist of stiffer chains that are connected to each other by hydrogen bonds. The disruption of hydrogen bonds during dry processing conditions contributes to fibre fibrillation. For large fibre fractions (larger than 3 mm), aerodynamic forces are less than gravity; therefore, their trajectory will not coincide with that of flows inside the grinding chamber.

Figure 6 presents the cross-sectional profile of the machine grinding unit and the grinding and secondary wood fibre flow distribution zone.

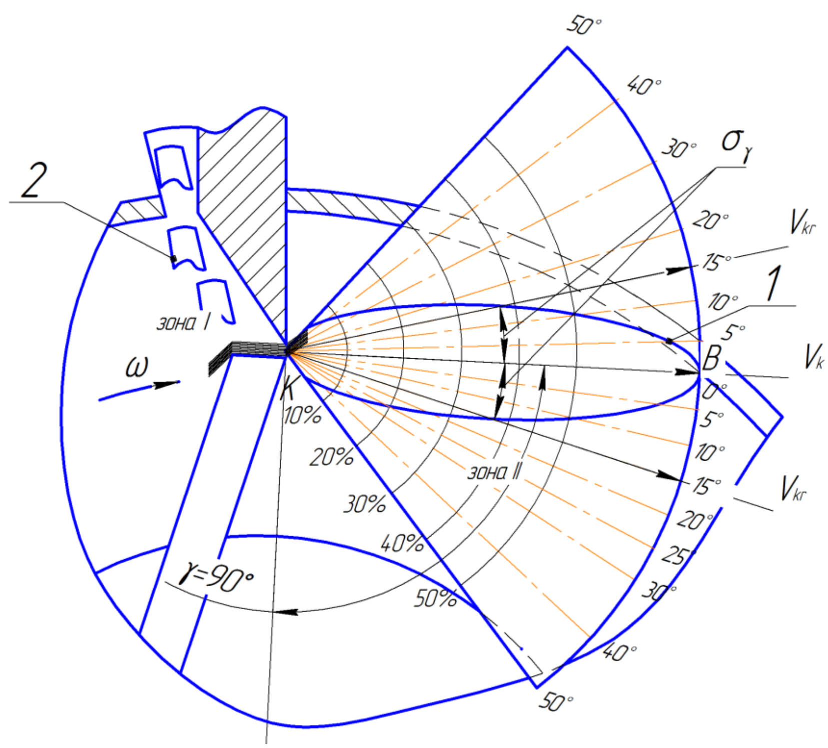

Fig. 6. Flow distribution of large wood fibres in Zone II (σ_{γ} is the mean square deviation K_{V}; V_{kr} is the tangent velocity of secondary wood fibres (m/s); *1* is the curve indicating the probability bounds of a secondary wood fibre flight in the intended direction; and *2* is wood fibre waste)

Figure 6 shows the direction of the ejected flow of wood fibre bundles coming out from the gap between the rotor and stator cutters onto the inner separator surface.

The fibrillation sector of the rotary cutting mill is taken as the space between the rotor cutter edges and the separator plane. As a result of penetration of the patches into the machine working zone, there was a movement of wood fibre wastes in the gap between the rotor and stator cutters in Zone II and a movement of fibres after the rotor cutter stroke in Zone II. Like a wood fibre bundle, a single wood fibre is a crystalline polymer developed at low temperatures. Having entered working Zone II, wood fibres moved along the tangent rotor circumference and hit the internal separator surface, thereby changing the vector direction. The further direction of the secondary wood fibre movement vector would be determined by the collision points with the rotor cutter, with each other, and with the separator and rotor body surface.

The line KV_k is the most probable average direction of a single wood fibre or fibre bundle flight determined by the geometric sum of velocities V_k and V_{kr}. The average velocity of secondary wood fibres in the most probable average direction KV_k was determined according to Eq. 5,

$$v_к = \sqrt{2gH(1 - \mu \cos \alpha_x)} \quad (5)$$

where g is the acceleration of free fall (m/s), H is the vertical drop height of secondary wood fibres (m), μ is the friction coefficient of wood fibre waste along the charging device wall, and $\varphi\pi$ is the feed angle of wood fibre waste into the grinding chamber (°).

The radii-vectors from the point K to the intersection with the curve *1* represent the probability densities of a wood fibre flight in the given direction. Different recovery coefficients depending not only on the elastic properties of materials but also on the shape and mass of colliding bodies, with irregular shapes and different sizes of wood fibres, resulted in a variation in reflection angles that increased as a result of other random factors in the grinding process. With strokes at velocities of 6 m/s to 64 m/s and incidence angles of 10° to 60° and with high-speed shooting, it was established that there is a rather close stochastic (probable) link between the reflection angle and the average ratio (on one side) and the incidence angle (on the other side) (Bauman *et al.* 1973),

$$К_\nu = \frac{\nu_к}{\nu} \quad (6)$$

where K_v is the velocity loss factor of secondary wood fibres when they hit the separator surface, and vv is the velocity of wood fibres rebounded off the separator (m/s).

As can be seen from Eq. 6, the stochastic link between the mean value of the ratio, which can be called the velocity loss factor of secondary wood fibres when they hit the separator surface K_v, and the incidence angle $\varphi\varphi$ is expressed by the empirical to Eq. 7,

$$К_\nu = \frac{1-k}{90°}\varphi + k \quad (7)$$

where k is the reference recovery coefficient, and φ is the incidence angle of secondary wood fibres (°). As can be seen from Eq. 7, $K_v = kK_v = k$ at $\delta_v = 0\delta_v = 0$ represents a quantity similar to the recovery coefficient of elastic deformations in polymers (in wood fibres). The flight directions of secondary wood fibres when they leave the working gap between the rotor and stator cutters are distributed according to the normal law with the distribution centre KV_k directed at the angle $\bar{\gamma} = \bar{\gamma} =$ 90° to the rotor radius and the mean square deviation $\sigma_\gamma = 22.3°$ (Chistova 2010), which can be taken as constant with sufficient accuracy, independent of the rotor rotation frequency and the gap between the rotor and stator cutters. The angle $\bar{\gamma}$ at V_p = 30 m/s was 90°, and it increased with an increase in circumferential velocity by approximately 4° for every 10 m/s. For practical calculations, $\bar{\gamma} =$ 90° can be taken regardless of the value of V_p.

The fractional composition of wood fibres ejected from the gap between the rotor and stator cutters was not identical, and it varied widely. The sizes of wood fibre fractions largely determine the direction and velocity of their movement.

The values K_v for individual secondary wood fibres vary with the mean square deviation $^{\sigma}K_v$, which decreased with an increase in the incidence angle in the following dependence to Eq. 8:

$$\sigma_{К\nu} = 0.17 - \frac{\varphi^2}{46800} \quad (8)$$

The kinetic energy of secondary wood fibres hitting the separator surface and the rotor cutter was partially spent on their fibrillation, and the higher this loss, the more energy was spent on fibre treatment. Equation 9 was used to calculate the energy loss of secondary wood fibres when they hit the inner separator surface, *i.e.*, the energy spent on fibrillation. Through relating the lost energy to the reserve of kinetic energy before hitting, the coefficient of use of the kinetic energy of secondary wood fibres (wood bundles) $m_k m_k$ by the mass for destruction was obtained:

$$К_э = \frac{\frac{m_k v^2}{2} - \frac{m_k v_k^2}{2}}{\frac{m_k v^2}{2}} = 1 - К_v^2 = 1 - \left[(1-k)\frac{\varphi}{90°} + k\right] \quad (9)$$

At the incidence angles $0 < \varphi < 15°$ $K_э = 0.91$ to 0.97, *i.e.*, from 91 to 97% of the energy reserve of secondary wood fibres can be used for destruction. At angles $\varphi < 15°$ $\varphi < 15°$, the coefficient $K_э$ decreases sharply. At an angle $\varphi < 0°$ $\varphi < 15°$, the effect of using the kinetic energy of secondary wood fibres would be maximum.

Thus, in the authors' opinion, wood fibres are destroyed in an dry grinding environment in the process of multiple collisions of the fibers against each other and against the walls and working bodies of the grinding plant. As a result, the accumulated energy on the surface of the fibers is directed to their fibrillation and destruction in the longitudinal direction. This makes it possible to save the length of the fibers (without shortening them) and reduce the diameter of the fibers, including small things.

The following are the results of studies in the form of statistical and mathematical equations with natural designations of factors describing the treatment of wood fibre waste from off-spec board products and waste from panel-sizing machines in fibreboard production. The obtained Eqs. 10 to 15 make it possible to establish quantitative dependencies of the dimensional-qualitative characteristics of secondary wood fibre obtained by the dry grinding method from the technological design parameters of the MR-4 grinding machine. All the equations were tested for adequacy using the Fisher's F-test. The coefficient significance was evaluated based on the methodology using the Student's t-test. The confidence probability was 95 to 99%. The coefficient of determination (R^2) was close to one (Borovikov and Borovikov 1998; Pizhurin and Pizhurin 2005). The governing equations are as follows:

– Grinding quality fractional indicator:

$$Fr_{WPF} = 41.45 + 0.61 \times z_{WPF} - 1.75 \times \varepsilon_{WPF} - 0.07 \times z_{WPF}^2 + 0.16 \times \varepsilon_{WPF}^2 - 0.03 \times z_{WPF} \times \varepsilon_{WPF} \quad (10)$$

$$Fr_{DPF} = 36.3 + 1.6 \times z_{DPF} - 1.5 \times \varepsilon_{DPF} - 0.2 \times z_{DPF}^2 + 0.11 \times \varepsilon_{DPF}^2 - 0.01 \times z_{DPF} \times \varepsilon_{DPF} \quad (11)$$

– Fibre-length-to-diameter ratio:

$$L/D_{WPF} = 60 + 4.6 \times z_{WPF} - 0.22 \times \varepsilon_{WPF} - 0.4 \times z_{WPF}^2 + 0.01 \times \varepsilon_{WPF}^2 - 0.01 \times z_{WPF} \times \varepsilon_{WPF} \quad (12)$$

$$L/D_{DPF} = 57.8 + 2.4 \times z_{DPF} - 0.37 \times \varepsilon_{DPF} - 0.3 \times z_{DPF}^2 + 0.01 \times \varepsilon_{DPF}^2 - 0.01 \times z_{DPF} \times \varepsilon_{DPF} \quad (13)$$

– Specific fibre surface area:

$$S_{WPF} = 487250 + 56008.1 \times z_{WPF} - 141640 \times \varepsilon_{WPF} - 5938 \times z_{WPF}^2 + 13702 \times \varepsilon_{WPF}^2 + 447 \times z_{WPF} \times \varepsilon_{WPF} \quad (14)$$

$$S_{DPF} = 320510 + 19078.2 \times z_{DPF} - 47579 \times \varepsilon_{DPF} - 2536 \times z_{DPF}^2 + 4288.3 \times \varepsilon_{DPF}^2 + 300.3 \times z_{DPF} \times \varepsilon_{DPF} \quad (15)$$

Figures 7 and 8 present the graphical dependencies based on the models obtained with natural factor values.

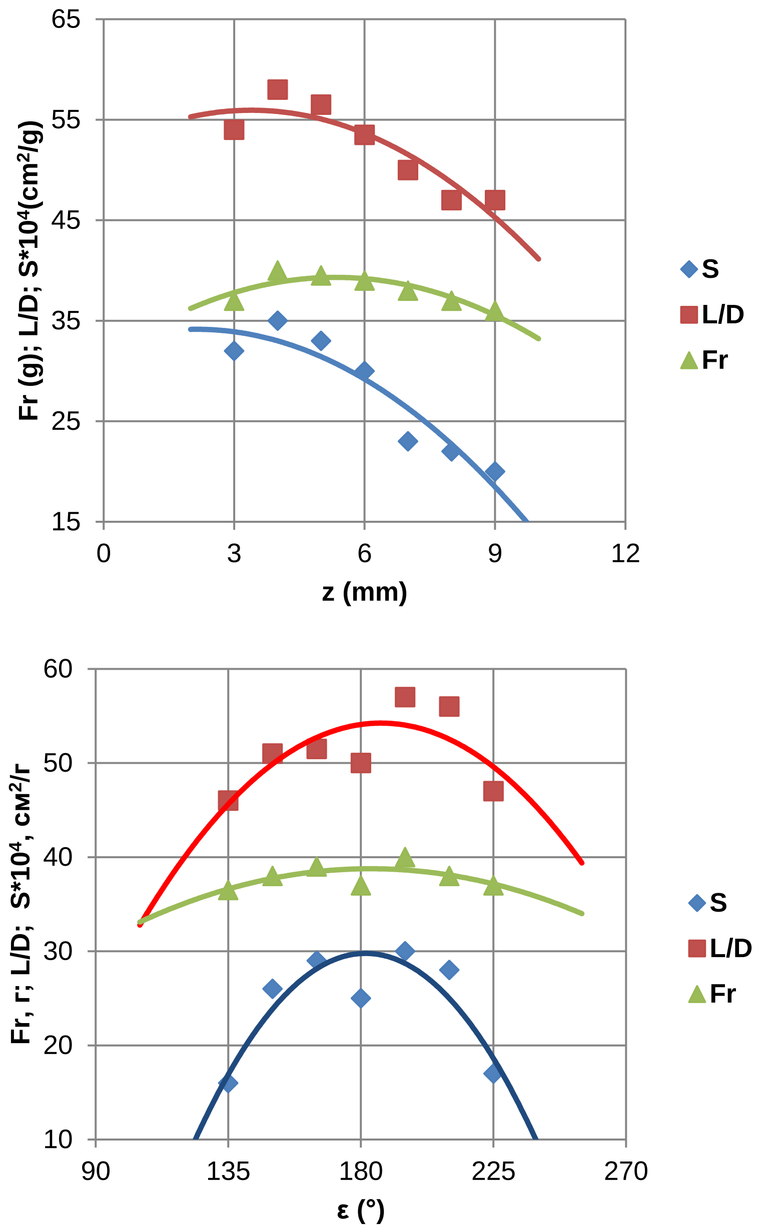

Fig. 7. Dependence of dimensional-qualitative characteristics of secondary wood fibres (obtained from wet process fibreboard waste) on the parameters under study

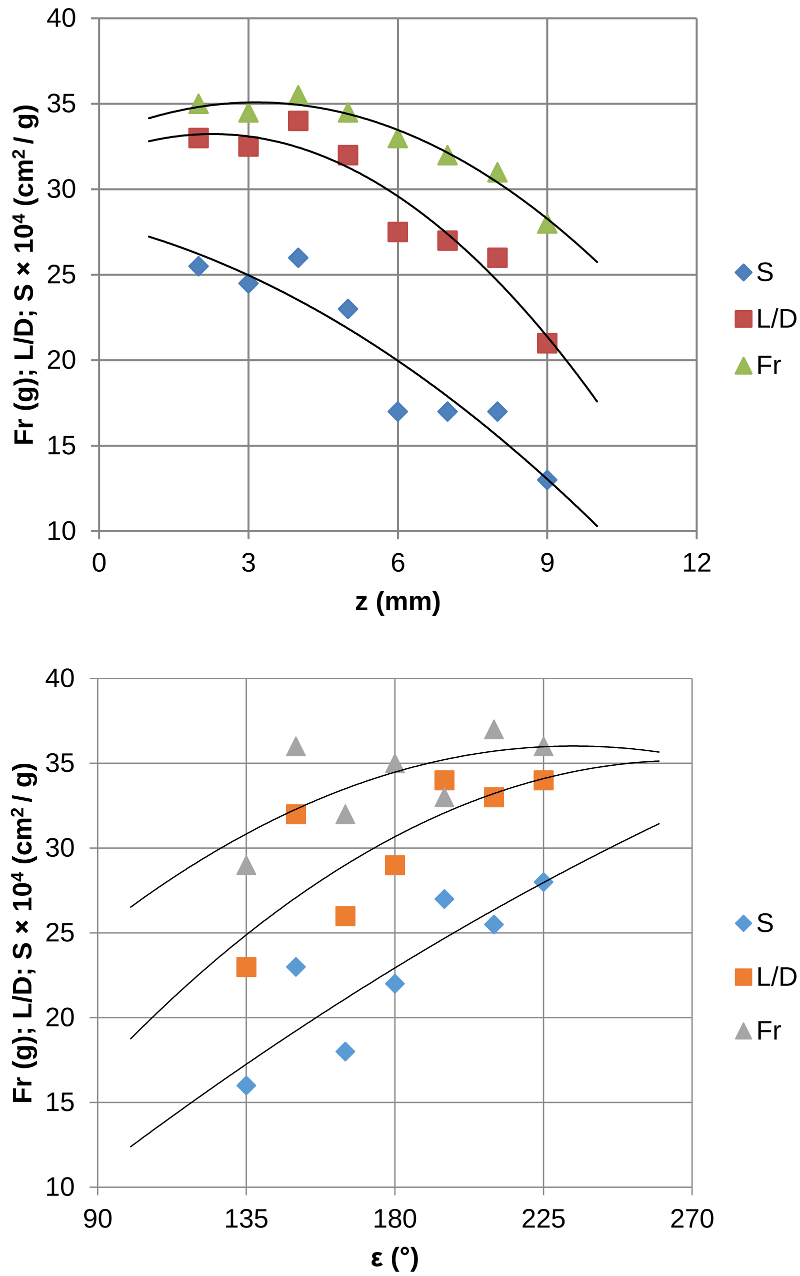

Fig. 8. Dependence of dimensional-qualitative characteristics of secondary wood fibres (obtained from MDF wastes) on the parameters under study

In analysing the results (Fig. 2a), it can be noted that the values of the factors under study generally improved with an increase in the gap between the rotor and stator cutters from 3 to 6 mm, and they tended to deteriorate with a further increase. The best values for the grinding quality fractional indicator (40 to 42 g) were recorded at z = 4 to 6 mm, the fibre-length-to-diameter ratio (56 to 58) at z = 4 to 5 mm, and the specific fibre surface area (320,000 to 350,000 cm^2/g) at z = 3 to 5 mm. It is impractical to set a gap of less than 2 mm and more than 10 mm between the rotor and stator cutters in view of the deterioration of the wood fibre pulp quality characteristics. With a decreased working gap between the rotor and the stator cutters, such phenomena as cutting, chopping, and crushing that contribute to the shortening of fibres prevailed, which was undesirable for the previously cut fibres. With an increased gap, the separation of wood fibre waste took place only due to the processes of dry grinding environment in the mill working chamber, which was not enough to treat well-developed wood fibre pulp capable of bonding.

Figure 8b shows the graphical dependencies based on the results of the same factors under study on the angle of the stator cutter contact with raw materials. At minimum values of this angle (135 to 180°), all qualitative characteristics increased to varying degrees. The best values for the grinding quality fractional indicator (38 to 40 g) were recorded at an angle of the stator cutter contact with raw materials ε = 180 to 200°, a fibre-length-to-diameter ratio (53 to 54) – at ε = 170 to 190°, and a specific fibre surface area (300,000 to 310,000 cm^2/g) – at ε = 180 to 200°. With an increase in the angle of the stator cutter contact with raw materials above 200°, the values of the wood fibre pulp quality characteristics deteriorated.

The angle of the stator cutter contact with raw materials also plays a decisive role in wood fibre waste treatment by dry grinding, because the stator cutter performs several functions at the same time. The position of the stator cutter in the grinding plant contributes to the uniform distribution of raw materials to be ground.

Similarly, the dimensional and qualitative characteristics of the wood fibres obtained during the MDF grinding can be analysed (Fig. 3).

Studies have shown that during wet grinding, secondary wood fibers are pre-heat treated at high temperatures and pressure. Wood fiber waste takes the form of so-called "inactivated" fibers. These fibers are not able to restore strong fiber-to-fiber bonds in the resulting finished products due to the so-called "irreversible keratinization" (Chistova 2010; Morozov *et al.* 2015). And with dry grinding, even a fiber with keratinization has signs of internal fibrillation.

The research results confirmed that an improved quality of the wood fibre semi-finished products obtained from fibreboard waste using the rotary cutting machine is achieved by changing the percentage of fibre fractions in press pulp.

CONCLUSIONS

1. The influence of the defibering of wood fibre wastes in a dry grinding environment on the dimensional-qualitative characteristics of secondary wood fibres is from the collision of secondary wood fibres with each other in the grinding chamber. The effect of the accumulation of a set of stresses and energy of single secondary wood fibres allows main cracks to be obtained and contribute to the formation of external and internal fibrillation in the absence of temperature and high pressures.
2. In this research, the essence of the treatment of wood fibre waste in a dry grinding environment was determined. Mechanical impact on wood fiber waste occurs due to cross-cutting (cutting, crushing, flattening, and breaking) and dry processing conditions (dissolution, fibrillation). This contributes to the formation of external and internal fibrillation of secondary wood fiber and increase the specific surface area in the absence of high temperatures and pressure, without the addition of chemical additives, without the use of water and steam.

3. The experimentally confirmed theoretical studies allow for the substantiated use of this method for the treatment of secondary wood fibre semi-finished materials in an dry grinding environment and to fully use them in the production of finished products.
4. A dry grinding plant can be used in production conditions for the treatment of secondary wood fibre semi-finished products. This grinding method will reduce labour costs for their treatment and the specific consumption of electricity, on average, to 40%, as well as the cost of finished products.

ACKNOWLEDGEMENTS

The authors express their gratitude to the Centre for Collective Use of KSC SB RAS for supporting this research. This work was carried out under the State Assignment issued by the Ministry of Education and Science of Russia for the project: "Technology and Equipment for the Plant Biomass Chemical Processing" by the Plant Material Deep Conversion Laboratory (Subject No. FEFE-2020-0016).

REFERENCES CITED

Ackermann, K., Götsching, L., and Pakarinen, H. (2000). "The potential of recycled fiber in papermaking" in: *Recycled Fiber and Deinking*, L. Göttsching, and H. Pakarinen (Eds.), Fapet Oy, Helsinki, Finland, pp. 358-438.

Alashkevich, Y. D. (1980). *Fundamentals of the Theory of Hydrodynamic Phenomena in the Process of Grinding Fibrous Materials*, Ph.D. Dissertation, Leningrad Institute of Technology of the Cellulosic and Paper Industry, Leningrad, Russia.

Bauman, V. A., Streltsov, V. A., Kosarev, A. I., and Slutsker, A. S. (1973). *Rotary Crushers*, Mashinostroenie, Moscow, Russia.

Bektas, I., Guler, C., Kalaycioglu, H., Mengeloglu, F., and Nacar, M. (2005). "The manufacture of particleboards using sunflower stalks (*Helianthus annuus* L.) and poplar wood (*Populus alba* L.)," *Journal of Composite Materials* 39(5), 467-473. DOI: 10.1177/0021998305047098

Borovikov, V. P., and Borovikov, I. P. (1998). *STATISTICA. Statistical Analysis and Data Processing in Windows*, Filin Publishing House, Moscow, Russia.

Chen, Z., Zhang, H., He, Z., Zhang, L., and Yue, X. (2019). "Bamboo as an emerging resource for worldwide pulping and papermaking," *BioResources* 14(1), 3-5. DOI: 10.15376/biores.14.1.3-5

Chistova, N. G. (2010). *Recycling Wood Waste in Fiberboard Production*, Ph.D. Dissertation, Siberian State Technological University, Krasnoyarsk, Russia.

Chistova, N. G., Morozov, I. M., Yakimov, V. A., Alashkevich, Y. D., and Zyryanov, M. A. (2015). "Production of wood-fiber plates by dry method of production, manufactured with the use of wood-fiber waste from format-trimming machines," *Chemistry of Plant Materials* 2015(4), 119-124. DOI: 10.14258/jcprm.201504852

Chistova, N. G., Rubinskaya, A. V., Matygulina, V. N., Zyryanov, M. A., Aksenov, N. V., Petrova, A. A., and Morozov, I. M. (2018b). "Method and device for the preparation of raw materials in the production of building materials," Utility Model Patent No. 2671141.

Chistova, N. G., Zyryanov, M. A., Matygulina, V. N., Aksenov, N. V., and Shinkevich, I. V. (2018a). “Device for fibrillation and separation of fibrous materials,” Utility Model Patent No. 2657685.

EN 622-5 (2009). “Fibreboards - Specifications - Part 5: Requirements for dry process boards (MDF),” European Committee for Standardization, Brussels, Belgium.

Ferritsius, O., Ferritsius, R., and Rundlöf, M. (2018). “Average fiber length as a measure of the amount of long fibers in mechanical pulps – Ranking of pulps may shift,” *Nordic Pulp & Paper Research Journal* 33(3), 468-481. DOI: 10.1515/npprj-2018-3058

Goncharov, V. N. (1990). *Theoretical Basics of Grinding Fibrous Materials in Cutting Machines*, Ph.D. Dissertation, Leningrad Technological Institute of Pulp and Paper Industry, St. Petersburg, Russia.

Gorazdova, V. V., Dernova, E. V., Dulkin, D. A., and Okulova, E. O. (2018). “The effect of fiber brushing and shortening when beating on the strength, deformation and fracture toughness properties of cellulosic materials,” *Lesnoy Zhurnal [Forestry Journal]* 2, 109-121. DOI: 10.17238/issn0536-1036.2018.2.109

Hazrati-Behnagh, M., Zarea-Hosseinabadi, H., Daliri-Sosefi, M., Abginehchi, Z., and Hemmati, A. (2016). “Mechanical and insulating performances of ultralight thick particleboard from sugarcane residues and woods planer shaving,” *European Journal of Wood and Wood Products* 74(2), 161-168. DOI: 10.1007/s00107-015-0989-7

Heinemann, S., Saharinen, E. T., Särkilahti, A., and Salminen, L. I. (2016). “The effect of wood alignment on wood grinding – Part 2: Fines character and microscopic observations,” *BioResources* 11(1), 2526-2535. DOI: 10.15376/biores.11.1.2526-2535

Hiziroglu, S., Jarusombuti, S., Bauchongkol, P., and Fueangvivat, V. (2008). “Overlaying properties of fiberboard manufactured from bamboo and rice straw,” *Industrial Crops and Products* 28(1), 107-111. DOI: 10.1016/j.indcrop.2008.01.002

Ihnát, V., Lübke H., Russ A., and Borůvka, V. (2017). “Waste agglomerated wood materials as a secondary raw material for chipboards and fiberboards. Part I. Preparation and characterization of wood chips in terms of their reuse,” *Wood Research* 62(1), 45-56.

Interstate Standard No. 2081 (2010). “Carbamide. Specifications,” Interstate Technical Committee for Standardization, Moscow, Russian Federation.

Interstate Standard No. 2184 (2013). “Sulphuric acid for industrial use. Specifications,” Interstate Council for Standardization, Metrology and Certification, Moscow, Russian Federation.

Interstate Standard No. 4598 (2018). “Fibre boards by wet way of production. Specifications,” Interstate Council for Standardization, Metrology and Certification, Moscow, Russian Federation.

Interstate Standard No. 14231 (1988). “Urea-formaldehyde resins. Specifications,” Ministry of Chemical Industry of the USSR, Moscow, USSR.

Interstate Standard No. 23683 (1989). “Petroleum paraffin waxes. Specifications,” Ministries of the Oil Refining and Petrochemical Industry of the USSR, Moscow, USSR.

Khider, T. O., and Hubbe, M. A. (2018). “Towards rational utilization of indigenous plant resources,” *BioResources* 13(4), 7172-7174. DOI: 10.15376/biores.13.4.7172-7174

Kozhukhov, V. A. (2015). *Grinding of Fibrous Semi-finished Products in Grinding Knife Machines at Impact on Fiber*, Ph.D. Dissertation, Siberian State Technological University, Krasnoyarsk, Russia.

Laleicke, P. (2018). "Wood waste, the challenges of communication and innovation," *BioResources* 13(2), 2182-2183. DOI: 10.15376/biores.13.2.2182-2183

Laskeev, P. K. (1967). *Wood Pulp Production*, Lesnaya Promyshlennost, Moscow, Russia.

Leonovich, A. A. (2003). *Physical and Chemical Bases of the Formation of Wood-Based Boards*, Khimizdat, St. Petersburg, Russia.

Li, B., Li, H., Zha, Q., Bandekar, R., Alsaggaf, A., and Ni, Y. (2011). "Review: Effects of wood quality and refining process on TMP pulp and paper quality," *BioResources* 6(3), 3569-3584. DOI: 10.15376/biores.6.3.Li

Liptsev, N. V. (1982). *Theoretical Foundations of the Technology of Wood-fiber Mass and Ways to Improve the Efficiency of the Production of Wood-fiber Boards,* Ph.D. Dissertation, Leningrad Forestry Academy, Saint Petersburg, Russia.

Mancera, C., El Mansouri, N., Pelach, M. A., Francesc, F., and Salvadó, J. (2012). "Feasibility of incorporating treated lignins in fiberboards made from agricultural waste," *Waste Management* 32(10), 1962-1967. DOI: 10.1016/j.wasman.2012.05.019

Mandelkern, L. (1964). *Crystallization of Polymers*, McGraw-Hill, New York, NY, USA.

Matygulina, V. N. (2007). *Preparation of Wood Fiber for Fiberboard Production by Dry Method*, Ph.D. Dissertation, Siberian State Technological University, Krasnoyarsk, Russia.

Matygulina, V., Chistova, N., and Marchenko, R. (2021). "Using various grinding equipment for the preparation of recycled wood fibre," *BioResources* 16(2), 2433-2447. DOI: 10.15376/biores.16.2.2433-2447

McDonald, D., Ouellet, D., Tchepel, M., Wild, P., Provan, J., and Jeffrey, D. (2014). "Wood mechanics: From chips to flocs to fibers - Part I," *Journal of Science & Technology for Forest Products and Processes* 4(5), 23-30.

Ministry of Industry and Trade of Russia (2018). "Order of the Government of the Russian Federation of September 20, 2018 No. 1989-r On the strategy for the development of the Forest Complex of the Russian Federation until 2030," Government of the Russian Federation, Moscow, Russia.

Moezzipour, B., Ahmadi, M., Abdolkhani, A., and Doosthoseini, K. (2017). "Chemical changes of wood fibers after hydrothermal recycling of MDF wastes," *Journal of the Indian Academy of Wood Science* 14, 133-138. DOI: 10.1007/s13196-017-0198-6

Morozov, I. M. (2016). *Preparation and Use of Fiberboard Waste in the Production of Fiberboard*, Ph.D. Dissertation, Siberian State Technological University, Krasnoyarsk, Russia.

Nicewicz, D., and Leszek, D. (2010). "Recycling of insulation boards by reuse," *Annals of Warsaw University of Life Sciences - SGGW Forest and Wood Technology* 72, 57-61.

Pizhurin, A. A., and Pizhurin, A. A. (2005). *Scientific Research Foundations*, MGUL Moscow State University of Forestry, Moscow, Russia.

Saharinen, E., Särkilahti, A., Salminen, L. I., and Heinemann, S. (2016). "The effect of wood alignment on wood grinding - Part 1: Properties of pulp and fines revealed in the grinding mechanism," *BioResources* 11(2), 4201-4211. DOI: 10.15376/biores.11.2.4201-4211

Şahin, H. (2020). “The potential of using forest waste as a raw material in particleboard manufacturing,” *BioResources* 15(4), 7780-7795. DOI: 10.15376/biores.15.4.7780-7795
Shi, S. Q. (2007). “Diffusion model based on Fick’s second law for the moisture absorption process in wood fiber-based composites: Is it suitable or not?,” *Wood Science and Technology* 41(8), 645-658. DOI: 10.1007/s00226-006-0123-4
Smith, S. (1922). *Rational Roll Theory* (Teil I), Otto Ernst Publishing House, Berlin, Germany.
Solikhin, A., Hadi, Y. S., Massijaya, M. Y., and Nikmatin, S. (2017). “Morphological and chemo-thermal changes of oven-heat treated oil palm empty fruit bunch fibers during dry disk milling,” *Journal of the Indian Academy of Wood Science* 14, 9-17. DOI: 10.1007/s13196-016-0182-6
State Standard of the USSR No. 2210 (1973). “Ammonium chloride for industrial use. Specifications,” Ministry of Chemical Industry of the USSR, Moscow, USSR.
Theng, D., El Mansouri, N., Arbat, G., Ngo, B., Delgado-Aguilar, M., Pèlach, M. A., Fullana-i-Palmer, P., and Mutjé, P. (2017). “Fiberboards made from corn stalk thermomechanical pulp and kraft lignin as a green adhesive,” *BioResources* 12(2), 2379-2393. DOI: 10.15376/biores.12.2.2379-2393
Vititnev, A. Y. (2019). *Improving the Process of Grinding Fiber Semi-finished Products in the Production of Wood-fiber Boards*, Ph.D. Thesis, Siberian State Technological University, Krasnoyarsk, Russia.
Wan, H., Wang, X., Barry, A., and Shen, J. (2014). “Recycling wood composite panels: Characterizing recycled materials,” *BioResources* 9(4), 7554-7565. DOI: 10.15376/biores.9.4.7554-7565
White, E. H. (2011). “Sustainable biofuels from forests: Woody biomass,” *Forests* 2, article no. 983. DOI: 10.3390/f2040983
Wu, Y. (2016). “Acceleration of bamboo forest base construction for bamboo pulp and development of bamboo, pulping and papermaking,” *Paper and Papermaking* 35(5), 48-50. DOI: 10.13472/j.ppm.2016.05.012
Yano, B. B. R., Silva, S. A. M., Almeida, D. H., Aquino, V. B. M., Christoforo, A. L., Rodrigues, E. F. C., Carvalho Junior, A. N., Silva, A. P., and Lahr, F. A. R. (2020). “Use of sugarcane bagasse and industrial timber residue in particleboard production,” *BioResources* 15(3), 4753-4762. DOI: 10.15376/biores.15.3.4753-4762
Zamagni, A. (2012). “Life cycle sustainability assessment,” *The International Journal of Life Cycle Assessment* 17(4), 373-376. DOI: 10.1007/s11367-012-0389-8
Zyryanov, M. A. (2012). *Obtaining Semi-finished Products in One Stage of Grinding for the Production of Wood-fiber Boards by Wet Method*, Ph.D. Dissertation, Siberian State Technological University, Krasnoyarsk, Russia.

Article submitted: July 2, 2021; Peer review completed: September 11, 2021; Revised version received: October 3, 2021; Accepted: October 18, 2021; Published: October 20, 2021.
DOI: 10.15376/biores.16.4.8152-8171