Mechanical Treatment of Raw Waste Lumber an Effective Way to Preserve the Ecology and Resources

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Abstract. Alternative process flowsheet machining of the machining of raw waste lumber were analysed, and it was implemented in a real machine model based on the chosen scheme. The forming process of the treated surface of the stock material was examined, and consequently the mathematical models of the geometric errors in terms of independent factors of the profile milling process were defined. Based on these models is possible to construct a treatment process of the raw waste lumber with minimal errors on the surfaces which were treated. The manufacturing of products from raw waste lumber allows to reduce the volume of deforestation and helps to preserve the ecology and economize the material resources.

1. Introduction

A significant portion of the surface of the planet "Earth" is covered by forest, which plays a crucial role in the maintenance of the ecological balance, and, therefore, the conditions of existence of all life on the planet. At the same time, the wood is a unique material, which, thanks to its properties, is widely used in various sectors of the national economy. To satisfy the global market demands for wood products requires large volumes of wood-stock material, and this involves an intensive deforestation. Despite the application of modern technologies in the timber enterprises [1] significant amounts of wood waste are formed, which are not used for its original purpose.

Annually the wood-processing enterprises of the Russian Federation generate millions of cubic meters of barks, slabs, laths and other waste wood, of which they produce mainly wood pellets and industrial wood chip. However, the raw waste lumber consist of the highest quality peripheral wood grain from which it is appropriate not to make fuel, but the products of the original purpose: pieces of furniture, products for interior decoration, construction of modern houses, etc. The machining of the raw waste lumber and the production of quality wood products on this basis allow to reduce the irrational use of wood, save material and energy resources [2], stabilize and improve the environmental situation through the conservation of natural forestlands as a basis for the regeneration of oxygen and natural barrier for dust and sand storms, which turn oases into deserts.

The raw waste lumber are characterized by an unpredictable shape and sizes, heterogeneity of the properties of the threated material [3], the stochastic disposition of knots and the lack of developed technological bases, which provoke serious difficulties in their machining and to some extent explains the reason for the lack of high-performance of engineering processes for a deep wood recycling. In conditions of the mentioned instability to guarantee a high machining efficiency and obtain accurate finished products from raw waste lumber is problematic. Consequently, there is a necessity of the development of high-performance processes on scientific substantiation and equipment for machining raw waste lumber, which allows, in addition to what has been said above, to get a significant economic effect and increase the competitiveness of woodworking companies in the conditions of the today's market [4].

For machining peripheral segments remaining after the logs slitting, it is used a special equipment. The known equipment leaves considerable waste after cutting, including peripheral segments smaller and does not allow to optimize constantly the treatment regimens in the process changing of the cutting conditions.

2. Justification and implementation of the process flowsheet of machining raw waste lumber.

The authors have developed alternative process flowsheet of machining raw waste lumber, which have analysed the simplicities of a practical implementation of the flowsheet and resonance-free processing conditions from the perspective of a stable blank locating, on the basis of the selected flowsheet (figure 1), which more than any other satisfies the above criteria. The flowsheet is characterized by a content of machining steps: the milling of the unbarked curved surface and the subsequent cutting of the curvilinear lateral edges are performed simultaneously on one machine. As processing guide base, the machine for forming the unbarked working surface is selected, and further the one for milling the blank surface, which provides the greatest length of the processing guide base and eliminate defects of the blank during the treatement.

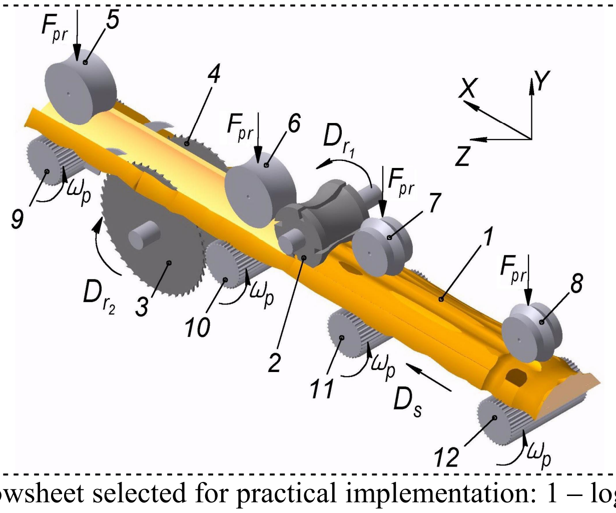
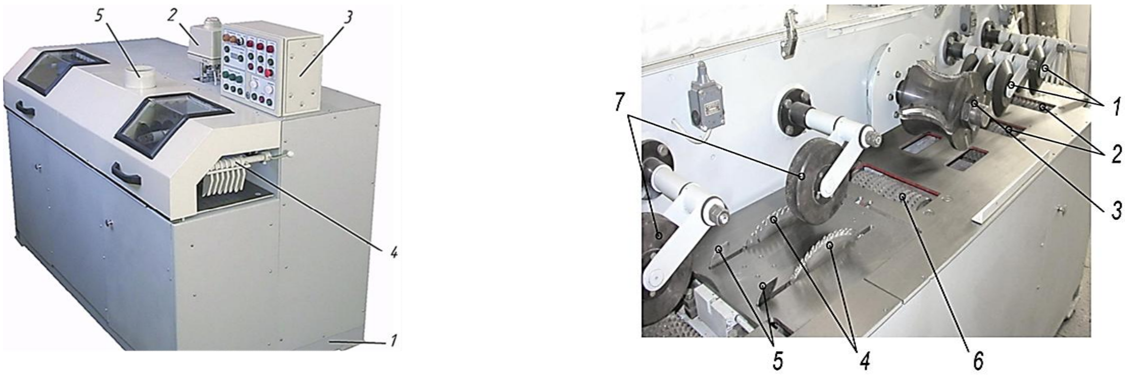


Figure 1. The process flowsheet selected for practical implementation: 1 – logging residues; 2 – form-milling cutter; 3-4 – saw wheels; 5-8 – pinch rollers; F_{pr} – pressing force; 9-12 – toothed rolling mill; ω_p – angular velocity of the rolling mill; D_{r1}, D_{r2}, D_s – working tool and stock material movement.

On the basis of the chosen scheme, the method and machine tool were developed for machining the raw lumber waste, equipped with a system of automatic speed control for supplying the working stock material and a device for cutting. The automatic speed control for supplying the working stock material allows to stabilize the cutting power, avoid the machine tool overloading and the cutting tool damage at the unexpected appearance of knots or an overrate allowance on the cutting zone, and it stably operate at a jump cutting depth up to 15 mm, which satisfies the average change of the peripheral segments allowance.

The machine tool for machining the raw waste lumber (figure 2a) includes a base 1, a drive 2 of vertical motion of the slide mill, a control unit 3, claw-type protection 4 and exhauster system 5 for removal residues.



a b

Figure 2. General view (a) and a working area (b) of the machine tool for machining raw waste lumber.

The rollers 1 are designed for clamping the stock material to the rolling mills 2 and 6 (figure 2b), the last move the stock material relatively to the rotating form-milling cutter 3, which removes the allowance from the unbarked surface stock material. The saws wheels 4 cut off the irregular side edges of the stock material, and the machined part of which is directed by the profiled rollers 7.

3. Analysis of the surfaces forming in the profile milling process of the raw waste lumber.

The developed equipment can be effectively used in the production, if they provide the high geometric accuracy to the finished products. Thereupon, we analyse the mechanism of the machined surfaces forming under the influence of kinematic and dynamic treatment process factors and determine the ways to reduce the geometrical errors, which arise during the profile milling of the unbarked surface of the raw waste lumber [5].

The material utilization coefficient will be maximized at removing it from the unbarked curved surface of the peripheral segment of the minimum allowance, which is achieved by a grinding cutting of the mill blade along a circumference KLM (figure 3) with the radius R_{pn} . The form-milling cutter is characterized by the current radius $R \in [R_{min}, R_{max}]$ The minimum radius R_{min} is located in the transversal plane of symmetry of the mill, and the maximum, R_{max} in the planes of both faces.

During the milling of the stock material with a cylindrical mill, the geometry error due to the kinematics of the milling process is described by the equation [6]:

$$\Delta = R - \sqrt{R^2 - \left(\frac{\pi S}{z\omega}\right)^2}, \quad (1)$$

where *R* is the radius of the cutting mill surface; *S* is the cutting feedrate of the raw material; $z\omega$ is the number of teeth and angular velocity of the mill respectively.

For the form-milling cutter the radius *R* of the cutting surface varies in height *B*, which leads to the formation of the cutting blade along different geometrical errors of the transversal stock material section. We determine the change of these errors, and for this we consider the contacting interaction of the form-milling cutter and the stock material (figure 3).

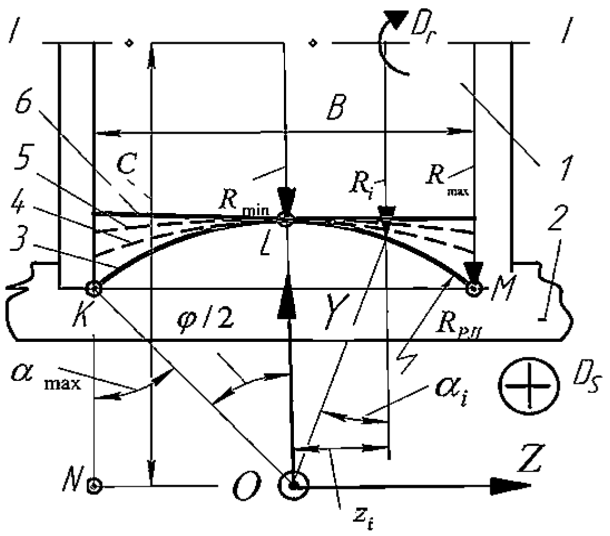


Figure 3. Scheme of contact interaction of the mill and the stock materail: 1 - form-milling cutter, 2 - stock material, 3 - curvilinear contour of the cutting blades 4-6 - contours of the cutting blade at a radius change of sharpening; R_{pn}, D_r, D_s - working motion of the tool and the stock material.

Distance from the center *O* of the circumference arc *KLM* to the axis I - I mill 1

$$C = R_{min} + O \cdot L = R_{min} + R_{pn} \tag{2}$$

In the current i-th transversal section of the mill, spaced at a distance z_i from the origin *O* of the coordinate system *YOZ*, the mill radius $R = R_i$, and the equation (2) of this section is given as:

$$C = R + R_{pл} \cdot \cos\left(\arcsin\left(\frac{z_i}{R_{pл}}\right)\right). \tag{3}$$

Equalling the right sides of (2), (3) and completing the conversion, we get:

$$R = R_{pn}\left(1 - \cos\left(\arcsin\left(\frac{z_i}{R_{pл}}\right)\right)\right) + R_{min} \tag{4}$$

The current angle α_i, is formed by the plane of the perpendicular tool axis and the radius R_{pn} of the cutting blade

$$\alpha_i = \arcsin\left(\frac{z_i}{R_{pn}}\right) \tag{5}$$

The numerical values of the angle $\alpha_i \in [0, \alpha_{max}]$, where $\alpha_{max} = 0{,}5\varphi$; φ – the central angle which corresponds to the arc of the circumference *KLM*. At the angle $\alpha_i = \arcsin\left(\frac{z_i}{R_{pn}}\right) = 0$ the coordinate

$z_i = 0$, and the plane perpendicular to the tool axis pass through the point L. In accordance with (4) at $z_i = 0$ the mill radius is equal to the minimum value R_{min}. At $\alpha_i = \alpha_{max} = \pm 0{,}5\varphi$ we have two transversal sections, one of which passes through the point *K*, and the other the point *M*. These sections are arranged symmetrically to the axis *Y*. The mill radius takes the maximum value R_{max} in these sections according to (4), which can be determined if the known minimum radius and height of the mill:

$$R_{\max} = R_{pn}\left(1-\cos\left(\arcsin\left(\frac{z_i}{2R_{pn}}\right)\right)\right) + R_{\min} \tag{6}$$

The expression (4) allow us to determine the radius of the mill in any of its transversal section at a known minimum radius R_{min} and the sharpening radius of the cutting blade R_{pn}. If it is known the maximum radius R_{max}, the radius of the cutting blade sharpening R_{pn} and height *B*, so you can define R_{min}, i.e. to solve the inverse problem. The radius of the cutting blade is set by the working drawings products, manufactured from a peripheral segment. If are given R_{max}, R_{min} and α_{max}, so the radius of the cutting blade

$$R_{pn} = \frac{R_{max} - R_{min}}{1-\cos\alpha_{max}}. \tag{7}$$

The central angle corresponding to the arc of the circumference *KLM* of the cutting blade is found from the equation:

$$R_{pn}\cos\alpha_{\max} = R_{pn} - (R_{\max} - R_{\min}) \tag{8}$$

Solving the equality $\alpha_{max} = 0{,}5\varphi$ the central angle

$$\varphi = 2\cdot\arccos\left(1-\frac{R_{max}-R_{min}}{R_{pn}}\right) = 2\cdot\arccos\left(\frac{B}{2R_{pn}}\right) \tag{9}$$

The contour of the cutting blade, delineate according to circumference *KLM*, is described by the equation:

$$Y^2 + Z^2 = \left(\frac{R_{max}-R_{min}}{1-\cos\left(\arcsin\left(\frac{B}{2R_{pn}}\right)\right)}\right)^2, \quad -\frac{B}{2} \le Z \le +\frac{B}{2} \tag{10}$$

By (4) - (9) we can determine the radius of the form-milling cutter in any transversal section, as well as to establish the relation between its main structural elements. After substituting (4) into (1) and completing the conversion, we obtain a mathematical model which describes the geometric error of the peripheral segment, which pass the profile milling:

$$\Delta = -R_{pn}$$

$$\Delta = -R_{pn}\cos\left(\arcsin\left(\frac{z_i}{R_{pn}}\right)\right) - \sqrt{\left[-R_{p\text{л}}\cos\left(\arcsin\left(\frac{z_i}{R_{pn}}\right)\right) + R_{\min} + R_{pn}\right]^2 - \left(\frac{\pi S_x}{Z_\omega}\right)} + R_{\min} + R_{pn} \tag{11}$$

The function (11) has not an extremum, so the graphics of the dependence of Δ on independent factors of the process was made: minimum radius of the mill $R_{min} = 20$; 35; 50; 65; 80; 100; 120 mm; radius of the cutting blade $R_{pn} = 100$; 150; 200; 250; 300; 350; 400; 450; 500; 550; 600; 650 mm; cutting feedrate of the stock material S = 300; 600; 900; 1200; 1500; 1800 mm/s; number of teeth of the mill Z = 4; 6; 8; 10; 12 pieces.; angular velocity of the mill ω = 300; 400; 500; 600; 700; 800 rad/s; current value of coordinates Z_i = 0; 20; 40; 60; 80; 100; 120 mm; height of the mill B = 100; 120; 140; 160; 180; 200 mm. The variation range of the values of these factors include the vast majority of the cutting conditions used in the processes of mechanical wood treatment.

Increasing the minimal radius R_{min} of irregularities formed during the milling process of the profiled surface of the stock material, the height is reduced (figure 4a), which is explained by the approaching of the intersection point of the adjacent cut to the treated surface.

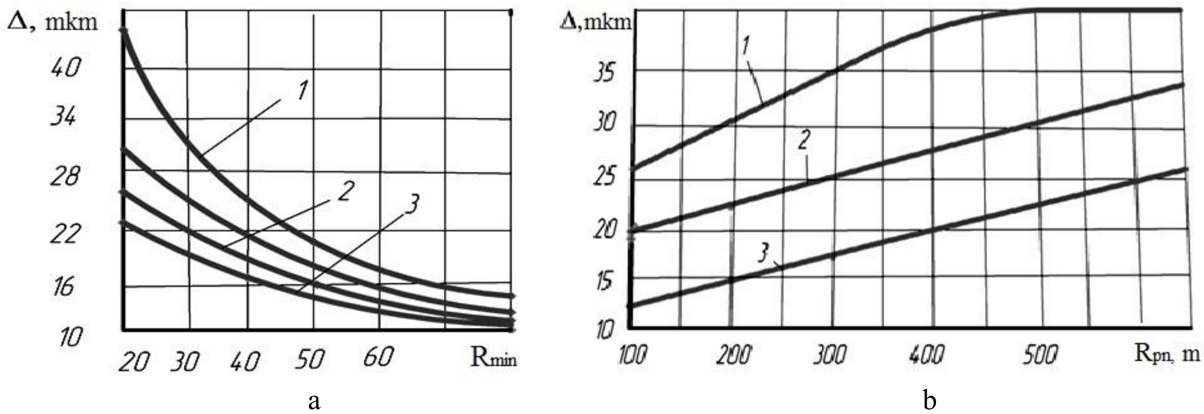


Figure 4. Influence of the minimal radius R_{min} (a) and the radius of the cutting blade sharpening R_{pn} (b) mill on the machined surface accuracy.

The curves 1-3 are described by the equation (12), which at the automated calculation software environment ADVANCED GRAPHER the factor R_{min} is replaced by the argument x, and the error Δ on the value of the function *Y (x)*. The number of the curve in figure 4a corresponds to the number of the following equation:

1. $$Y(x) = -200\cos\left(\frac{50}{200}\right) - \left(\left(-200\cos\left(\frac{50}{200}\right) + X + 200\right)^2 - 2.465\right)^{\left(\frac{2}{4}\right)} + X + 200$$

at R_{pn} =200 mm; $B = 100$; $S_x = 100$ mm/s; $Z = 4$; $\omega = 500$ rad/s;

2. $$Y(x) = -100\cos\left(\frac{75}{100}\right) - \left(\left(-100\cos\left(\frac{75}{100}\right) + X + 100\right)^2 - 2.465\right)^{\left(\frac{2}{4}\right)} + X + 100 \qquad (12)$$

at R_{pn} =100 mm; B=150 mm; $S_x = 1000$ mm/s; $Z = 4$; $\omega = 500$ rad/s;

3. $$Y(x) = -150\cos\left(\frac{75}{150}\right) - \left(\left(-150\cos\left(\frac{75}{150}\right) + X + 150\right)^2 - 2.465\right)^{\left(\frac{2}{4}\right)} + X + 150$$

at $R_{pл}$ =150 mm; $B = 100$; $S_x = 100$; $Z = 4$; $\omega = 500$ rad/s.

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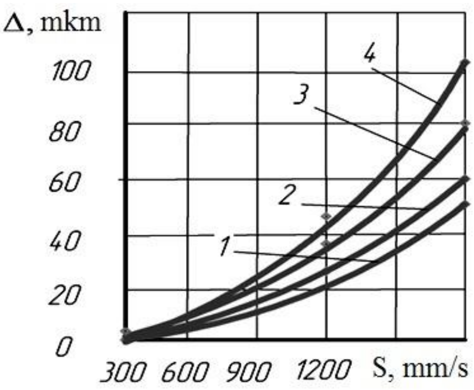
From the figure 4a and (12) it follows that to increase the accuracy of the surface after the profile milling of the stock material the radius R_{min} should be increased. The radius increase of the sharpening R_{pn} of the cutting blade leads to an increase in the geometric accuracy Δ of the treated surface. At the values R_{pn} = 100...350 mm the error Δ change linearly (figure 4b), increasing R_{pn} from 350 mm to 500 mm and Δ rise in accordance with the curve, but at $R_{pn} > 500\,\text{mm}$ Δ is stabilized at the maximum value (the curve 1 becomes parallel to the abscissa axis). The character of the curves 2 and 3 is similar to curve 1 with the difference that the sections are parallel to the abscissa and are arranged at a more remote distance from the origin of the coordinates distance.

As the increase of R_{pn} the current mill radius decreases, the contour of the cutting blade 3 is straightened (figure 2, curves 4, 5), reaching its limit position as a straight line 6, for which $R_{pn} = \infty$, that is the mill changes from profile into a cylindrical form with a radius. R_{min}. This explains the increase in error Δ during the rise of the sharpening radius R_{pn}.

The increase of the speed of the longitudinal feed S of the stock material leads to increment of the distance between the adjacent unit cuts [7, 8], the removal of the cut point of intersection from the treated surface and the rise of errors Δ (figure 5a). To improve the geometric accuracy of milled profiled surface, the feeding should be reduced [9, 10].



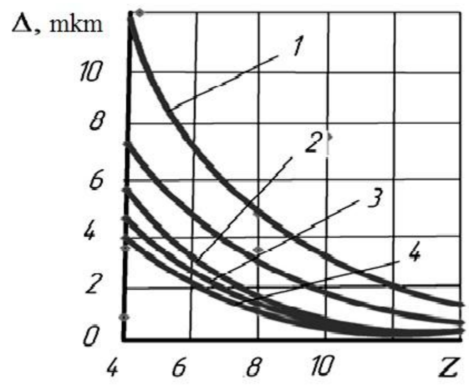
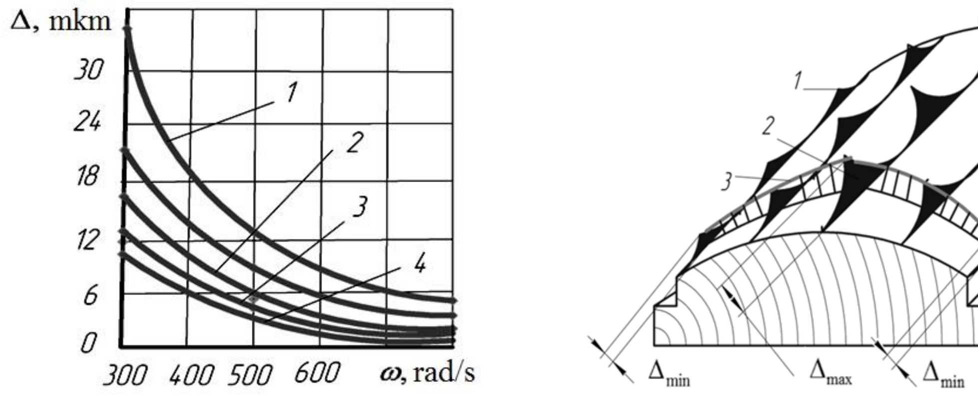


Figure 5. Influence of the cutting feedrate S of the stock material (a) and number of teeth z of the mill (b) to the error of the treated surface.

The increase of the number of cutting teeth of the profiled mill causes a reduction of the geometric errors of the treated surface (figure 5b), which is explained by a decrease in the time between the adjacent cuts, the reduction of the load on each tooth and a quieter work of the technological system. The number of teeth z shows a less influence on the kinematic error of the machined surface in comparison with other considered process factors.

During the increment of the angular velocity ω of the mill, the error Δ is reduced (figure 6a), which is associated with a decrease in the application time of the adjacent cuts, as well as the distance $\frac{2\pi \cdot S}{z\omega}$ between the points of intersection of the cuts [11]. The curves 1-4 characterize the change in error of the machined surface at different input kinematic factors of the process.



a b

Figure 6. Influence of the mill angular velocity on the error (a) and disturbance of the errors on the treated of the profiled product surface (b): 1 - minimal error; 2 - maximal error; 3 - curve that defines the change in error in the transversal section.

However, it should be noted that the increase of ω, inevitably leads to the rise of the unbalanced centrifugal force $Q = m\omega^2\rho$, (m is the unbalanced mass instrumenta, ρ is the distance from the rotational axis to the unbalanced mass). At high angular velocities ω, even a small unbalanced mass *m* becomes a source of great value to the centrifugal force *Q*, causing fluctuations in the technological system [12, 13]. This creates a situation in which the reduction of the errors Δ by increasing ω leads to an rise of geometric errors due to the deterioration of the dynamics of the milling process. In addition, during the increment of ω the necessity for more accurate balancing of the tool increase, which leads to an additional labour costs. The increment of the height B of the mill causes a small reduction in errors [14].

Based on these equations and graphics, it was built a 3D-model of the geometric distribution errors on the machined profiled product surface (figure 6b). In the transversal section of the final product, the value of the error Δ is variable. The minimal error Δ_{min} occur at the edges of the product, and the maximal Δ_{max} in the middle, where the allowance is removed by the teeth of the minimal radius R_{min}. In the direction from the middle to the edges of the product, the errors are reduced according to the curve 3. The analysis of the geometric errors of the profiled product surface showed that at an incorrect construction of the milling process of the raw waste lumber on the treated surface generate significant irregularities in the height (4 mm or more).

Using the ADVANCED GRAPHER software analogous to the expression (12), the mathematical model errors was obtained Δ as a function of the radius of the cutting blade sharpening, R_{pn}, the cutting feedrate of the stock material *S*, the number of teeth z and the angular velocity ω of the mill, which allows to manage independent factors of the process to ensure the minimal error of the treatment. To minimize the geometric errors due to the kinematic profiled milling, it is necessary to increase R_{min}, ω and *z*, and also reduce R_{pn} and *S*.

At the profiled milling of the blank material in addition to the kinematic factors, also the dynamic ones act as principal vector and principal moment of the imbalances of the cutting tool and discrete milling force [15]. Under the action of the mill imbalances, the treated surface is formed as a sinusoidal surface, the error Δ_1 was formed by the end of the mill, which was removed from the leading foot of the of the console and Δ_2 by the close end to the front support (figure 7).

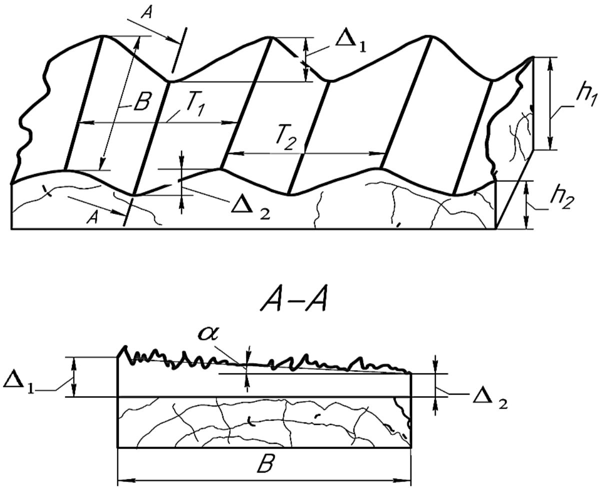


Figure 7. 3D - model of the surface treated by the unbalanced mill.

Error $\Delta_1 > \Delta_2$, treated profile inclined toward the horizontal plane at an angle, α , size $h_1 > h_2$ and pitch $T_1 - T_2$. The current sinusoidal error was made due to imbalances mills,

$$\Delta_i = \frac{D_{CT}\omega^2}{J_B}(1 \pm tg\alpha), \tag{13}$$

where D_{CT} is the main vector of the imbalances mills; ω is the angular velocity of the mill; J_B is the stiffness of the spindle node with a perpendicular direction to the surface being treated. We receive a plus sign in (13) to the removed end from the front support of the mill, and negative one the to end, located close to the front support.

The geometrical error in an arbitrary *i*-th transversal section of the profiled mill was made due to the action of the milling force,

$$\Delta_{резі} = \frac{(J_B + J_3)P \cdot \cos\left[\frac{\pi}{2} - \text{arctg}\left(\frac{P_y}{P_z}\right) - 2\arcsin\left(\sqrt{\frac{t}{D\phi}}\right)\right]}{J_B J_3} \cdot (1 \pm \text{tg}\alpha), \tag{14}$$

where J_3 is the stiffness of the stock material in a perpendicular direction to the treated surface; P_y, P_z is the radial and the main component of the milling force $P = \sqrt{P_y^2 + P_z^2} \cdot t$ - is the milling depth; $D\phi$ is the current mill diameter.

The total geometric error of the treated surface includes the kinematic Δ_k and dynamic components Δ_{d1}, Δ_{d2}. The Δ_{d1} component is determined by the centrifugal force *Q* and the bending moment of inertia M, caused by imbalance mills, and the component Δ_{d2} by the discrete milling force P_{cut} (figure 8).

The sinusoid 1 formed by the vectors *Q* and M drive the burst 2 of the elastic displacements caused by the action of discrete milling forces P_{cut}, as well as tracks the cuts 3 left by the mill teeth. Pitch of the sinusoidal error Δ_{d1} is larger than the error Δ_{d2} in z times, z- is the number of the cutting teeth.

The thick curve line 4, which envelopes the error delineations Δ_k, Δ_{d1} and Δ_{d2}, constitutes the final profile of the longitudinal section of the machined surface formed by the tool imbalances, kinematic factors and shock pulses of the cutting tool teeth.

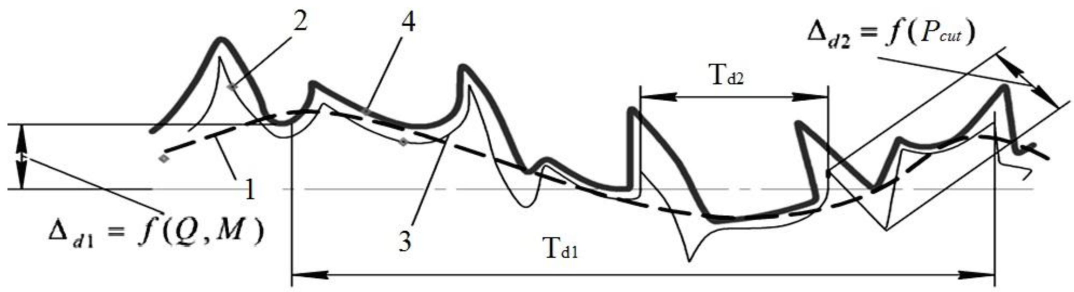


Figure 8. The profile of a longitudinal section of the treated surface is formed by the action of the kinematic and dynamic factors of the profile milling process of the raw waste lumber.

The analysis of the dynamics of the formation of geometrical errors in the longitudinal section under the action of the cutting tool imbalances showed that the value of the imbalances affect the height of the irregularities, and the angle of the principal vector and the principal moment of imbalance affects only the errors dislocation according to the machined surface. In order to reduce the errors caused by the imbalances, it is necessary to make the adjustments on the profiled mill masses, and for the errors caused by the cutting force to use the automatic power control of the milling.

The mathematical models of the geometrical errors of the treated surfaces were experimentally confirmed and are the basis for the development of an efficient machining process of the raw waste lumber. The designed and manufactured machine tool passed the validation in an accredited laboratory conditions, of which was received a document, which certifies its compliance with requirements according to the results. The machine tool and the treating raw waste lumber process were tested in production conditions with a positive result.

The widespread use of the developed equipment and technology in the timber enterprises will provide not only the saving in material and energy resources, but also improves the ecological environment by preserving forests in a permanently developing world of technological civilization.

4. Conclusion.

1. To ensure a high geometrical precision of the products from raw waste lumber, the profiled surface, the stock material and its geometrical errors were investigated, and the results showed that the disclosed mechanisms impact the kinematic and dynamic milling process factors on the final accuracy of the machined surfaces. On the basis of the obtained and experimentally validated mathematical models we can to predict the accuracy of the finished product in a wide range of the changes of the independent factors of the profile milling process, and to control the magnitude of the geometrical errors.
2. In order to minimize the geometric errors of the machined surface due to the kinematics of the profile milling and cutting tool geometry, it is necessary to increase the angular velocity ω, the number of cutting teeth z, the height B and the minimal radius R_{min} of the mill, and to reduce the radius of sharpening of the cutting blade R_{pn} and the cutting feed rate S of the stock material.
3. The reduction of the geometric error, caused by the discrete cutting force, is achieved by using a machine tool of the automatic power control of the milling and cutting feedrate control of the stock material. The widespread use of the developed equipment and machining process of the raw waste lumber will allow to obtain accurate products from raw waste lumber, saving material and energy resources, and it will help to preserve the forests on the planet.

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