Theoretical justification for the development of computer model of MDF structure and its milling process

T V Efimova¹ and T L Ischenko

Department of Mechanical Wood Technology, Voronezh State University of Forestry and Technologies named after G.F. Morozov, 8 Timiryazeva Street, Voronezh 394613, Russian Federation

¹E-mail: tanechka-ef@rambler.ru

Abstract. The main parameter for determination of quality of MDF board processing after milling is roughness of the surface. The well-known models of wood cutting are unsuitable for the assessment of this parameter, since they make it possible to draw only qualitative conclusions about the roughness, they do not allow calculating the numerical value. To calculate the roughness value, the model must take into account the structure of the material and the main parameters affecting the roughness. The purpose of this work is to substantiate the development of a computer model of the MDF structure and the process of its milling using the finite element method. The implementation of this approach will allow, according to the specified parameters of the cutter and modes of its operation, to determine the quality and energy indicators of the milling process from a theoretical point of view. As a result of the work carried out, a detailed theoretical justification for the development of a computer model of MDF structure and the process of its milling was given. Its implementation makes it possible to determine the quality and energy parameters of the milling process according to the specified parameters of the cutter and its operating modes.

1. Introduction

Medium density fiberboard (MDF) is widely used in furniture production and interior decoration [1, 2, 3]. MDF have good physical and mechanical properties; it is excellently processed and finished [4]. MDF is classified as an environmentally friendly material that can really replace natural wood. This material is mainly made from wood waste, which naturally contributes to the preservation of forests and nature. The peculiarity of MDF is the complete absence of phenol in the composition, which has a toxic effect on the human body. MDF are very popular in the world construction and furniture market. It is worth noting that their affordable cost, which is much less than the cost of natural wood, as well as excellent technological properties, make this material very popular and relevant.

Many enterprises that manufacture MDF cabinet furniture are faced with the problem of the surface quality after milling. The main parameter determining the quality of MDF board processing after milling is roughness of the surface. The well-known models of wood cutting are unsuitable for the assessment of this parameter, since they make it possible to draw only qualitative conclusions about the roughness, but do not allow calculating the numerical value [5, 6, 7]. For the calculation of the roughness value, the model must take into account the structure of the material and the main parameters that affect the roughness.

Today, there is a significant number of works by Russian and foreign researchers devoted to
improving the quality of processing wood-based panel materials [8, 9, 10]. Based on the analysis of the literature, it has been established that the main parameters determining the value of the roughness of the milled surface of MDF boards are speed of the blade along the material surface and supply of material to the tooth, as well as the angular parameters of the tool and the density of the boards [10, 11, 12].

In the physics of materials, when modeling the internal structure and internal processes of complex bodies, as a rule, the finite element method is used [13]. According to this method, a complex body is considered as a collection of a large number of small solid bodies (finite elements) that interact with each other and are capable of moving or distorting. Body behavior is described by a system of a large number of equations of the same type. Each equation describes the state of an individual finite element, and the numerical solution of the system is carried out using computer calculations.

The purpose of this work is to substantiate, from a theoretical point of view, the development of a computer model of the MDF structure and the process of its milling using the finite element method, the implementation of which will allow, according to the specified parameters of the cutter and modes of its operation, to determine the quality and energy indicators of the milling process.

2. Materials and methods

MDF (in its cross-section through thickness) in a computer model is represented by a combination of a large number of individual round elements (based on comparison with a circular cross-section of wood fibers) (figure 1). Modeling is performed in two-dimensional space X – Y. The exclusion of the third dimension makes it possible to increase the linear dimensions of the material specimen in the X and Y directions for a given number of elements (up to 8000 elements were used in the calculations). Circle elements are sections of fibers that lie across the cut. Fibers lying in the shear plane are represented as black serpentine complexes. This is a complex of circles with a more rigid connection between them. The figure shows the movement of the cutter on the MDF surface.

![Figure 1. Model of MDF board structure. 1 - MDF microlayer, 2 - cutting blade.](image-url)

The state of the i-circle element is characterized by four variables: the Cartesian coordinates of its center (x_i, y_i) and two components of the speed of the blade along the surface of the material (v_{xi}, v_{yi}) (figure 2).

When milling MDF, chips and wood dust are formed, therefore it is assumed that in the model the interaction of elements with each other will be viscoelastic. The elements of the material initially interact with each other, and when they move away from each other at a certain distance, separation occurs and the viscoelastic interaction is turned off.

The forces acting on the elements are calculated by the following method. Suppose that element is subjected to force from each of the surrounding elements j [14]:
The forces of elastic and viscous interaction of the elements $I$ and $j$; $N_e$ – the total number of elements in the material model.

The distance $r_{ij}$ between their centers $S_i(x_i, y_i)$ and $S_j(x_j, y_j)$ is calculated for each pair of elements:

$$r_{ij} = \left( (x_i - x_j)^2 + (y_i - y_j)^2 \right)^{1/2}$$  \hspace{1cm} (2)

Consider three different options for calculating the forces that arise as a result of the interaction between the elements of MDF fibers. The interaction is taken to be zero for fibers in a cross section. The interaction is assumed to be maximum one for fibers lying at an angle in the cross section. For fibers lying across and fibers lying at an angle, weak interaction is assumed.

1) If the elements $i$ and $j$ do not interact, then

$$F^E_{x_{ij}} = \begin{cases} c_w (d_e - r_{ij})(x_i - x_j) \\ \frac{r_{ij}}{r_{ij}}, & \text{if } r_{ij} < d_e \\ 0, & \text{if } r_{ij} \geq d_e \end{cases}$$

$$F^E_{y_{ij}} = \begin{cases} c_w (d_e - r_{ij})(y_i - y_j) \\ \frac{r_{ij}}{r_{ij}}, & \text{if } r_{ij} < d_e \\ 0, & \text{if } r_{ij} \geq d_e \end{cases}$$  \hspace{1cm} (3)

2) If the elements $i$ and $j$ interact weakly, then

$$F^E_{x_{ij}} = \begin{cases} c_w (d_e - r_{ij})(x_i - x_j) \\ \frac{r_{ij}}{r_{ij}}, & \text{if } r_{ij} < d_e + d_w \\ 0, & \text{if } r_{ij} \geq d_e + d_w \end{cases}$$

$$F^E_{y_{ij}} = \begin{cases} c_w (d_e - r_{ij})(y_i - y_j) \\ \frac{r_{ij}}{r_{ij}}, & \text{if } r_{ij} < d_e + d_w \\ 0, & \text{if } r_{ij} \geq d_e + d_w \end{cases}$$  \hspace{1cm} (4)
\[
F_{x_{ij}}^{E} = \begin{cases} 
(c_x(d_e - r_{ij})(y_i - y_j)) & \text{if } r_{ij} < d_e + d_w \\
0 & \text{if } r_{ij} \geq d_e + d_w 
\end{cases}
\]

3) If elements i and j interact strongly, then
\[
F_{x_{ij}}^{E} = \begin{cases} 
(c_x(d_e - r_{ij})(x_i - x_j)) & \text{if } r_{ij} < d_e + d_s \\
0 & \text{if } r_{ij} \geq d_e + d_s 
\end{cases}
\]

\[
F_{x_{ij}}^{E} = \begin{cases} 
(c_x(d_e - r_{ij})(y_i - y_j)) & \text{if } r_{ij} < d_e + d_s \\
0 & \text{if } r_{ij} \geq d_e + d_s 
\end{cases}
\]

Where \(F_{x_{ij}}^{E}\) and \(F_{y_{ij}}^{E}\) – Cartesian components of the force \(F_{ij}^{E}\),

- \(d_e\) – diameter of the elements;
- \(d_m, d_s\) – distance of overlapping in the elements with each other in case of weak and strong interaction;
- \(c_x\) and \(c_y\) – toughness of elastic interaction of the elements corresponding to weak and strong interaction.

When calculating \(F_{ij}^{V}\), a coefficient \((r_{ij} - (d_e + d_m))\) was introduced to take into account the mutual penetration of elements into each other.

\[
F_{x_{ij}}^{V} = k_m(r_{ij} - (d_e + d_m))(v_{x_i} - v_{x_j})
\]

\[
F_{y_{ij}}^{V} = k_m(r_{ij} - (d_e + d_m))(v_{y_i} - v_{y_j})
\]

Where \(v_{x_i}, v_{y_j}\) and \(v_{x_j}, v_{y_j}\) – Cartesian components of the speeds of the i-th and j-th element;

- \(k_m\) – damping factor.

In accordance with Newton’s second law, we write down the equations of motion of the i-th element:

\[
m_e \frac{d^2 x_i}{dt^2} = \sum_{j=1}^{N_e} (F_{x_{ij}}^{E} + F_{x_{ij}}^{V}) + c_e \cdot r_{int i} \cdot s_{x_i} + k_v(v_{x_i} - v)
\]

\[
m_e \frac{d^2 y_i}{dt^2} = \sum_{j=1}^{N_e} (F_{y_{ij}}^{E} + F_{y_{ij}}^{V}) - m_e \cdot g + c_e \cdot r_{int i} \cdot s_{y_i} + k_vv_{y_i}
\]

Where \(m_e\) – element mass;
- \(t\) – time;
- \(g\) – gravitational acceleration;
- \(c_e\) and \(k_v\) – coefficients of toughness and viscosity of the viscoelastic interaction of the i-th element with the cutter blade;
- \(r_{int i}\) – distance of mutual penetration of the i-th element and the blade;
- \(s_{x_i}\) and \(s_{y_i}\) – Cartesian components of a unit length vector indicating the direction of the force acting on the i-th element from the side of the blade;
- \(v_{x_i}\) and \(v_{y_i}\) – Cartesian components of the velocity of the i-th element;
- \(v\) – blade speed along the material surface.

Equations of the form (7) for all \(N_e\) elements characterize the change in the material over time.

Rotation of circle elements around their centers is not taken into account in the model. Rotation is taken into account automatically when moving large fragments.

During a computer experiment, elements can move inside a rectangle with dimensions \(L_X \times L_Y\) (figure...
1). Initially, the circles form a random tight packing. The cutter blade, moving along the OX direction, forces the MDF elements to move. A rough surface area is formed behind the knife (figure 1).

In this case, any element can go beyond the rectangle, that is, one of the conditions will be fulfilled: $x_i < 0, x_i > L_X, y_i < 0, \ y_i > L_Y$. Then the element returns to the rectangle by mirroring from the corresponding wall. If the condition $x_i > L_X$ is fulfilled, the $x_i$ coordinate of the element is assigned the value $x_i = L_X - (x_i - L_X)$, and the element velocity changes sign: $v_{xi} = -v_{xi}$.

The number of elements $N_e$ required for a given cross-sectional area $S$ obeys the quadratic law:

$$N_e = \frac{S}{k_p \cdot \pi \cdot d_e^2}$$

(8)

Where $k_p$ – packing factor of the circle elements.

The optimal diameter of the elements, which makes it possible to describe a material specimen with linear dimensions of 1–3 mm and does not lead to lengthy computer calculations, is 10 µm. Thus, the total number of elements in the model will be 8000 or more.

Before the computer experiment, the procedure for preparing a close-packed volume of material is performed. The required number of elements is distributed over the entire volume of the rectangle randomly. Then, the equations of motion (7) are integrated for 0.1 s. Under the action of the forces that arise between the elements, they begin to form a layer of material in the lower part of the rectangle. To create a dense packing, a “shake-up” is performed within 0.1–0.2 s: additional random displacements are reported to the coordinates $(x_i, y_i)$ of all the elements at each integration step. The speeds of the elements are gradually damped. The elements form a stationary dense-packed material by the end of the procedure.

Elements located at a distance less than $d_e + d_w$ are considered to be interacting one. The elements of the model interact in different ways (formulas 3–5). If the distance between any pair of elements becomes more than $d_e + 2d_w$, it is considered that the elements do not interact. Correction of the gluing pattern is made.

The fibrous MDF structure is taken into account through the use of elements grouped in black serpentine complexes (figure 1). Their number $n_f$ can be varied, thus changing the mechanical properties of the material and simulating the required MDF density.

The material elements interact with the cutter blade by viscoelastic forces. This is shown by two terms in the formulas (7). For the $i$-th element, it is checked that its centers $(x_i, y_i)$ are in a particular sector relative to the center of the blade $C$ $(x_C, y_C)$ (figure 3). For this, the angle $\varphi$ between the center of the element and the direction of movement relative to the center of the blade $C$ is determined.

$$\varphi = \tan^{-1} \left( \frac{y_i - y_C}{x_i - x_C} \right)$$

(9)

Figure 3. Blade sectors relative to blade center $C$ $(x_C, y_C)$: EB - segment of the rear edge of the blade, BA - segment of the tip of the blade, AD - segment of the front edge of the blade.
Depending on the value of the angle $\varphi$, one of three cases is implemented:

1) If $\varphi < \gamma$ and $\varphi > (\pi/2 - \alpha)$ (where $\gamma$ – front clearance angle, $\alpha$ – back angle of the blade), then the element is in sector 1 (interacts with the blade tip), we have:

$$r_{int i} = \frac{((x_i - x_C)^2 + (y_i - y_C)^2)^{1/2} - \rho - d_e}{2}$$

$$s_{x_i} = \cos \varphi; \ s_{y_i} = \sin \varphi$$

(10)

Where $\rho$ – blade tip radius.

2) If $\varphi > \gamma$ and $\varphi < (\pi/2 + \beta/2)$ (where $\beta$ – blade angle), then the element is in sector 2 (interacts with the front plane of the blade), we have:

$$r_{int i} = A_1 \cdot x_i + B_1 \cdot y_i + C_1 - \frac{d_e}{2}$$

$$s_{x_i} = \cos \gamma; \ s_{y_i} = \sin \gamma$$

(11)

where $A_1, B_1$ and $C_1$ – coefficients of the normalized equation of the straight line that simulates the front plane of the blade. The straight line is set at two points A and D (figure 3).

3) If $\varphi < (-\pi/2 - \alpha)$ and $\varphi > (\pi/2 + \gamma + \beta/2)$, then the element is in sector 3 (interacts with the back plane of the blade), we have:

$$r_{int i} = -A_2 \cdot x_i - B_2 \cdot y_i - C_2 - \frac{d_e}{2}$$

$$s_{x_i} = \cos \left(-\frac{\pi}{2} - \alpha\right); \ s_{y_i} = \sin \left(-\frac{\pi}{2} - \alpha\right)$$

(12)

where $A_2, B_2$ and $C_2$ – the coefficients of the normalized equation of the straight line simulating the rear plane of the blade. The straight line is set at two points B and E (figure 3).

If the $i$-th element partially falls into the blade area, then $r_{int i} > 0$, and the parameters $r_{int i}, s_{x_i}, s_{y_i}$ are involved in the calculations by the formulas (7).

To determine the variability of the material structure during the blade passage, it is necessary to integrate the equations of motion (7) with the substitution of forces calculated by the formulas (3-6) depending on the type of pair of interacting elements, as well as the parameters of interaction with the blade (formulas (10-12). The system is solved numerically by the Euler method [15].

The calculation of the kinematic parameters of milling: the speed of the blade along the surface of the material $v$, m/s, and the material feed per tooth $s_z$, $\mu$m, was carried out according to the well-known formulas [5]:

$$V = \frac{2\pi R_c n}{60}$$

(13)

$$S_z = \frac{v_s}{2\pi 10^{-6}}$$

(14)

where $n$ - tool rotation frequency, $\text{min}^{-1}$;

$R_c$ – cutter radius (for a profile cutter, the radius depends on the position along the cutter axis), m;

$v_s$ - tool feed rate, m/min.

The following parameters were calculated as the output parameters of the milling process: surface roughness $R_z$, $\mu$m, cutting power $N$, kW, and pressure under the blade $P$, N.

In a computer experiment, we take the interval from 0.8 mm to 2.2 mm as the base length. From henceforth, a roughness less than $R_z = 20$ $\mu$m is considered to be acceptable, which is necessary when veneering the MDF surface with thin decorative films. Thoroughness $R_z$ is determined by the formula:
$$R_z = \frac{1}{5} \left( \sum_{i=1}^{5} h_{\text{max}i} - \sum_{i=1}^{5} h_{\text{min}i} \right)$$  \hspace{1cm} (15)

where $h_{\text{max}i}$ - distance from the five highest points of the profile;

$h_{\text{min}i}$ - the distance from the five lowest points of the profile to the 0-0 baseline drawn parallel to the centerline and not crossing the profile.

The average cutting power $N$ determines the energy consumption of the milling process and thus determines the economic costs. The average cutting power in a computer experiment is determined as follows:

$$N = \frac{x_2 - x_1}{v} \int_{x_1}^{x_2} F_b(x) \, dx$$  \hspace{1cm} (16)

where $x_1$ and $x_2$ – the boundaries of the interval over which the power averaging is performed;

$v$ – blade speed along the material surface;

$F_b(x)$ – the total force exerted on the blade by all the elements interacting with it at a given position.

The pressure under the cutter blade $P$ characterizes the compressive action exerted by the blade on the material as it passes through it. The pressure is the average interelement interaction:

$$P = \frac{1}{N_c} \sum_{k=1}^{N_c} \left( F_{xk}^2 + F_{yk}^2 \right)^{1/2}$$  \hspace{1cm} (17)

Where $N_c$ – number of elements involved in the calculation; $F_{xk}$ and $F_{yk}$ – Cartesian components of the force acting on the element $k$ from the side of the surrounding elements.

Element $k$ is involved in the calculation if it is near the blade, that is, there is the inequality:

$$((x_k - x_c)^2 + (y_k - y_c)^2)^{1/2} < L$$  \hspace{1cm} (18)

Where $L$ – the compression radius of the structure, determined by the displacement of the elements under the action of the blade (in further calculations, we took $L = 100 \, \mu m$).

3. Results and discussion

A special computer program in the Object Pascal language was compiled in the Borland Delphi 7.0 integrated programming environment to solve the system of differential equations on the basis of the model, and for the convenience of carrying out various computer experiments with the model.

The program enables to carry out a computer experiment on cutting a layer of the material with a cutter blade. The program specifies the main parameters characterizing the material (the number and size of the elements, the coefficients of the interaction of the elements), the cutter blade (the front and rear angles, the sharpening radius, the interaction coefficients of the blade with the elements), the technological process (the speed of the blade and the feed per tooth). During the program operation, screen continuously displays: current image of the model material and the blade, current values of the main characteristics of the process: cutting power, pressure under the blade, as well as the diagram of forces on the cutter blade (figure 4). The integration of the motion equations is stopped after the blade passing and the surface roughness is calculated.

Thus, the computer model makes it possible to determine qualitative and energy indicators of the milling process (theoretically) according to the specified parameters of the cutter and the modes of its operation.
4. Conclusions
As a result of the work carried out, a theoretical justification for the development of a computer model of the MDF structure and the process of its milling was given, the implementation of which makes it possible to determine the quality and energy indicators of the milling process according to the specified parameters of cutter and modes of its operation.

The results obtained can be used in research on the development of optimal technological modes for processing board materials made on the basis of wood fibers. They can also enable to improve the quality of board material processing, as well as to improve the design of the cutting tool used for such processing.

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