INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN, 1/2014 (5): 40–47

EXAMINATION THE PROCESS OF LONGITUDINAL SOLID WOOD PROFILE MILLING. PART I: PERFORMANCE OF CUTTER PROFILE

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ABSTRACT

In this article the, process of longitudinal solid wood profile milling has been studied. In the first part of the article, an analysis is done with regard to: the profile of universal cutterhead used for experimental studies; the characteristics of the chips formation process by longitudinal milling; the influence of the feed per tooth and the accuracy of the cutter teeth placement on the quality of the processed surfaces. The conclusions will be used in the experimental investigation of the milling processes.

Key words: Multi-purpose profiling, profile cutter head, chips formation

INTRODUCTION

Milling process is widespread in the woodworking and especially in the furniture industry, using rotary cutters with rotational motion. Milling can be qualitative and productive only under conditions of optimum cutting regime, proper design and geometry of cutting tools.

The aim of the article in the I^{-th} part is to examine the profile of the experimental cutterhead, the influence of the feed per tooth and the accuracy of the placement of the teeth on the quality of the treated surfaces.

METHODS

For the studies, a multi-purpose profile cutterhead was used. It is with a limiter and tool body in aluminium of the company „Leitz“ (Germany) (Fig. 1). The main parameters of the cutterhead are given in Table 1.

Fugure 1: Multi-purpose profile cutterhead with limiter, tool body in aluminium: A – general view in assembled state, B – common type of disassembly.

Table 1: Basic parameters of the multi-purpose profile cutterhead

Profile cutterhead	
Identification №	ID 025685
Class	WM 500 1 04
Application	Profiling
Design	Mechanical knife clamping, non-adjustable; Aluminium body
Knives material	HSS
Thickness of knives (s), mm	4,0
Number of teeth (z)	2
Width of the hub (B_h), mm	41,0
Body width (B_b), mm	36,4
Width of the knife (B_k), mm	40,0
Body diameter (D_b), mm	93,0
Maximum diameter of milling (D_{max}), mm	121,0
Minimum diameter of milling (D_{min}), mm	96,0
Bore size (d), mm	30,0
Rake angle (γ), ^{0}	18,0
Sharpening angle (β), ^{0}	47,0
Clearance angle (α), ^{0}	25,0
RPM (n), min^{-1}	6000÷10000

The main research approach used in this paper is the method of logical-heuristic analysis of facts in the formulation of some general assumptions and hypotheses about the process of lengthwise profile milling of solid wood.

CHARACTERISTICS OF THE CHIP FORMATION PROCESS BY LENGTHWISE PROFILE MILLING

Several interaction zones are differed in the arc of contact during wood milling process. This depends on the relative position of the cutter teeth to the grain direction. Within each area, the conditions of wood milling are different, which affects the quality of the treated surfaces and cutting forces (Glebov 2005).

Figure 2 shows a scheme of grove formation by lengthwise wood milling. In the incision of cutter teeth in the wood at point A, the angle of contact (φ_c), measured between the velocity vector of main movement (V) and the wood grain direction is $\varphi_c = 0^0$. In this case there is lengthwise cutting, which change in lengthwise-perpendicular cutting. At point B, the angle of contact is equal to the cutting angle ($\varphi_c = \delta$) and the front face of the tooth is perpendicular to the wood fibers. The cutting is done in the central zone (C).

The wood fibers are cut in the section of the arc BC in the central zone $\delta \leq \varphi_\kappa \leq 90^0$ from the main cutting edge. Then its front side starts deforming the wood fibers. The milling process is carried out at more favorable conditions. Cutting resistance increases as milling comes to the frontal cutting, and reaches its maximum value at point C. With teeth dullness cutting the fibers becomes more difficult and they break in the fibers plane. Therefore, roughness and incompletely cut fibers remain on the machined surface.

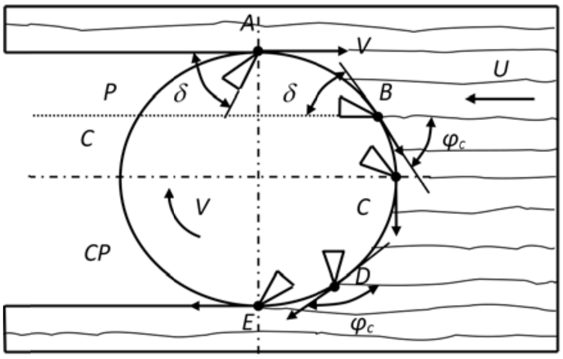


Figure 2: Lengthwise wood by zones:
P **–peripheral;** ***C*** **- central,**
CP **- Central-peripheral milling**

On the arc *AC*, counter milling runs at $0^{\circ} \leq \varphi_c \leq 90^{\circ}$. The milling from point *C* passes on the arc *CDE* from the central into central-peripheral (*CP*) zone. In this area, the cutting of wood fibers occurs at $\delta \leq \varphi_K \leq 180^{\circ}$. When the tooth enters the area of point *E*, the cutting passes from the frontal mode to lengthwise and cutting forces are reduced. Cutting conditions become more favorable, but teeth going out from the wood will break off if there is not enough compression on wood.

PROFILE MILLING

The profile milling is widely applied in the production of chairs, furniture, doors and windows, musical instruments and more. The profile of the cross section of the surface may be composed of individual straight and curved sections, in various combinations. The simplest case of profile milling is unilateral oblique (at angle ε) milling (fig. 3).

The cutting edge is inclined at an angle ε to the face of the cutter, whereat the cut of the wood makes a cross-section *ABCE* (fig. 3). Processed surface represented by the segment AB is formed at an angle. The special feature of the oblique milling is that every point on the cutting edge relates to specific features: radius of the cutting; depth of milling; contact angle, chip thickness; angle of convergence of fibers and also rake and clearance angle (Kryazhev 1979).

The contact angle for depth milling h_x, at any point *x* of the cutterhead diameter D_x (fig. 3) is defined by the equation:

$$\varphi_{c_x} = \arccos(1 - \frac{2h_x}{D_x}) \qquad \textbf{(1)}$$

The average chip thickness (e_{av_x}) would be:

$$e_{av_x} = u_z.\sin\frac{\varphi_{c_x}}{2}.\sin\varepsilon \qquad \textbf{(2)}$$

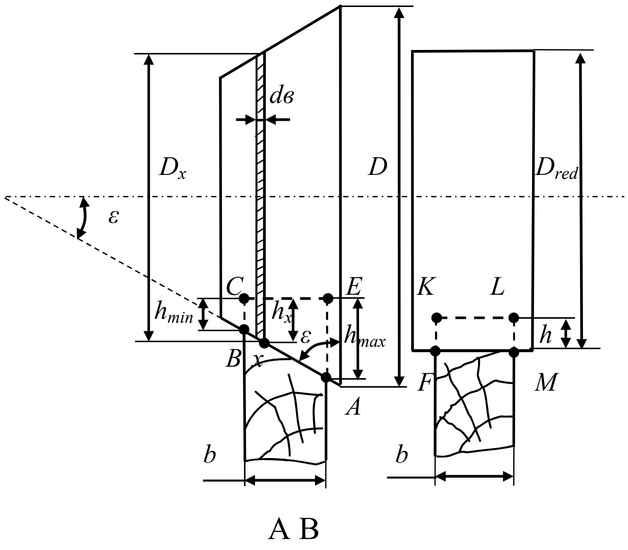


Figure 3: Unilateral oblique milling

The average value of the kinematic angle of convergence (θ_{av_x}) is:

$$\theta_{av_x} = \frac{\varphi_{c_x}}{2} \qquad \textbf{(3)}$$

The rake angle in the plane perpendicular to the cutting edge is:

$$\gamma_n = \arcsin(\frac{D}{D_x}.\sin\gamma.\sin\varepsilon) \qquad \textbf{(4)}$$

The clearance angle in the plane perpendicular to the cutting edge is:

$$\alpha_n = arctg(\frac{D}{D_x}.tg\alpha.\sin\varepsilon) \qquad \textbf{(5)}$$

The cutterhead diameter at unilateral oblique sharpening differs and, it can be represented as a set of infinitesimal cylindrical cutters with infinitely little width, having a common axis of rotation. Then, an infinitesimal width *db* of such a cylindrical cutter with diameter D_x, can be introduced and to calculate the average value of a kinematic or dynamic value, we can integrate all infinitesimal values of a given quantity the whole width of the cutter. However, it is a laborious process. For practical calculation a simplified method is used, the core of which is the substitution of the oblique cutting with cylindrical cutting (fig. 3 B).

In figure 3A, the area *ABCE* is replaced by the equivalent figure area *FKLM* (fig. 3 B). The milling depth *h* is determined by the equality of the two figures, i.e.:

$$h = \frac{h_{\max} + h_{\min}}{2} \qquad \textbf{(6)}$$

where h_{max} is the maximum milling depth at point A (fig. 3 A);

h_{min} - the minimum milling depth at point B (fig. 3A).

The reduced diameter of milling (D_{red}, fig. 3B) is:

$$D_{red} = D - \frac{b}{tg\varepsilon} \qquad \textbf{(7)}$$

where *D* is the nominal diameter of the cutter, m;

b – width of milling, m;

ε – slope angle of the cutting edge in relation to the front face of the cutter, ^{0}.

Contact angle (φ_c) is defined as in the case of cylindrical milling:

$$\varphi_c = \arccos(1 - \frac{2h}{D_{red}}) \qquad \textbf{(8)}$$

The average thickness of the chip (e_{av}) is determined taking into account the inclination of the cutting edge at an angle ε according to the equation:

$$e_{av} = u_z \sin\frac{\varphi_c}{2}.\sin\varepsilon \qquad \textbf{(9)}$$

The reduced values to the rake (γ_{red}) and clearance angle (α_{red}) are defined as:

$$\gamma_{red} = \arcsin(\frac{D}{D_{red}}.\sin\gamma.\sin\varepsilon) \qquad \textbf{(10)}$$

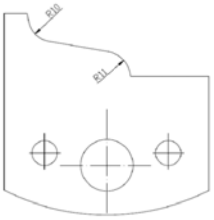
$$\alpha_{red} = arctg(\frac{D}{D_{red}}.tg\alpha.\sin\varepsilon) \qquad \textbf{(11)}$$

The average reduced cutting speed (V_{red}, m.s^{-1}) for D_{red} is defined as:

$$V_{red} = \pi.D_{red}.n \qquad \textbf{(12)}$$

DESCRIPTION OF THE CUTTERHEAD PROFILE

Figure 4 shows drawing of the experimental profile cutterhead. It shows that as a result of the profile, the radius of the milling is a variable. The maximum diameter is D_{max} = 121 mm, and the minimum one is D_{min} = 96 mm (figure 3.1 A). Furthermore, the profile consists of one straight profile and two sections with a radius of curvature *R* = 11 mm and *R* = 10 mm (figure 3.1 B).



A B

Figure 4: A – Profile cutterhead; B – profile knife

The profile of the cross section of the knife is represented as an unilateral oblique (at angle ε) milling, which is then replaced with cylindrical milling (fig. 5). In this case, the angle of inclination is ε = 70^o. The results from calculations for *h*; D_{red}; φ_c; γ_{red}; and α_{red} by formulas (6, 7, 8, 9, 10 and 11) are shown in table 2.

Table 2: Reduced values for profile cutter

The results of calculations for h, D_{red}, γ_{red}, α_{red}, β_{red} and φ_c											
h_{min} mm	h_{max} mm	h mm	D mm	b mm	$sin\varepsilon$	$tg\varepsilon$	D_{red} mm	$\gamma_{red}{}^{0}$	$\alpha_{red}{}^{0}$	$\beta_{red}{}^{0}$	$\varphi_c{}^{0}$
5,0	15,0	10,0	121,0	40,0	0,94	2,75	106,5	19,4	26,7	43,9	36,0

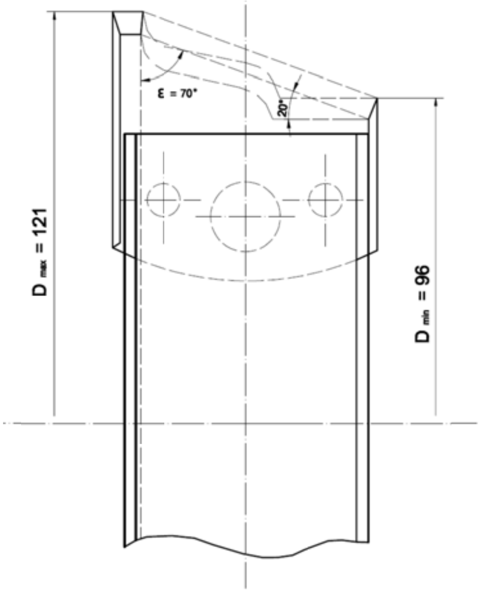


Figure 5: Transforming the profile cutter into the cutter for oblique (angled) milling

INFLUENCE OF FEED PER TOOTH AND ACCURACY OF THE TEETH LOCATION ON THE QUALITY OF THE MACHINED SURFACES

The roughness of the surface milled is determined by the depth of the bums and depends on the following factors (Philipov 1979):

- The geometric precision of the cutter, the quality of knives preparation and its proper placement and centering;
- The proper installation of the machine and its geometric accuracy;
- The deformation resistance of the machine elements and the vibration stability of cutting and based units;
- The kinematics of the milling process, as it is set in the machine.

The main types of roughnesses during the milling process are kinematic roughnesses. The crest of the waves is the intersection of two circles of cut. They are at a distance to one another corresponding to the feed per tooth (u_z) (Glebov 2007).

Figure 6 shows an example diagram of forming the surface of milling per one revolution of the cutterhead with two teeth. With that, suppose the tips of the teeth of the cutter are located on circles with different radii: as $R_1 > R_2$. The error of due to different placement of the tips of the cutter teeth will be:

$$\Delta_{1-2} = R_1 - R_2.$$

It is known that the trajectory described by each of the teeth in the milling process is cycloid. With that, kinematic roughness in the form of waves is formed on the surface finish. To simplify, we assume that the trajectory which the teeth described is a circle.

To determine the height of the crest of the kinematic waves, it is necessary to write the equations of the overlapping circles and find the points at which they intersect.

The equations of the circles 1 and 2 with the tooth radii of rotation R_1 and R_2 are:

$$\begin{cases}(x-0)^2+(y-R)^2=R_1^2, \\ (x-u_z)^2+(y-R)^2=R_2^2\end{cases} \qquad \textbf{(13)}$$

Solving the system of equations for an arbitrary pair of teeth, the following is obtained:

$$x_i=u_z(i-1)+\frac{\Delta(R_{1i}-\Delta)}{2u_z}+\frac{u_z}{2} \qquad \textbf{(14)}$$

where Δ is the inaccuracy of the teeth radius, mm ($\Delta=\Delta_{1i-2i}=R_{1i}-R_{2i}$);

i – number of teeth pair.

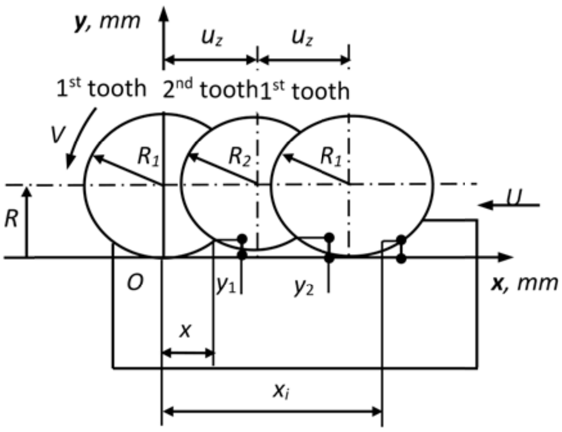


Figure 6: Forming the kinematic waves on surface during the milling process

For each pair of teeth we will get:

$$x=\frac{(R_1-R_2)(R_1+R_2)+u_z^2}{2u_z} \qquad \textbf{(15)}$$

The height of the wave crest for any pair of teeth will be:

$$y_i=R-\sqrt{R_{1i}^2-\left[\frac{u_z}{2}+\frac{\Delta(2R_{1i}-\Delta)}{2u_z}\right]^2} \qquad \textbf{(16)}$$

For each pair of teeth, the height of the wave will be:

$$y=R-\sqrt{R_1^2-\left[\frac{u_z}{2}+\frac{(R_1-R_2)(R_1+R_2)}{2u_z}\right]^2} \qquad \textbf{(17)}$$

From equations (14) and (16) it follows:

– If $R_1 = R_2$ ($\Delta = 0$), the crest of the wave is located at a distance $x=\frac{u_z}{2}$ from the center O_1; for the i-th pair of teeth:

$$x_i=u_z(i-1)+\frac{u_z}{2} \qquad \textbf{(18)}$$

- If $\Delta = 0$ ($R_1 = R_2$) for all the teeth, then the height of all the crests is the same and depends only on the feed per tooth (u_z); when $u_z = 0$, $y = 0$; when $u_z = 2R_1$, then y = R_1;

- If two neighbour circles of rotation of the teeth have the smallest radiii, they form the highest crests in the system of coordinate's xOy.

When solving inverse problems, it is necessary to find feed per tooth (u_z) for a specific roughness. Solving equation (16) we obtain:

$$u_z=\sqrt{R_1^2-(R-y)^2}-\sqrt{R_1^2-(R-y)^2-\Delta(2R_1-\Delta)} \qquad \textbf{(19)}$$

When $R = R_{\max} = R_1$, then feed per tooth (u_z), mm is:

$$u_z=2\sqrt{y(2R-y)} \qquad \textbf{(20)}$$

Furthermore, from (20) it follows:

$$u_z = \sqrt{y(2R-y)} + \sqrt{y(2R-y) - \Delta(2R-\Delta)} \tag{21}$$

Suppose that for a profile cutterhead used (fig. 1, table 1), which has a reduced diameter

D_{red} = 106,5 mm, the reduced radius of the tooth is $R = R_1$ = 53,3 mm, R_2 = 53,25 mm. We need to determine the coordinates of the crest of kinematic waves and roughness of the milled surfaces.

The output data and the calculated results are shown in table 3.6.

For surface roughness $R_{z\ max}$ = 56 μm obtained for Scots pine and $R_{z\ max}$ = 63 μm for common beech (Part II of the article) at $R = R_{max} = R_1$, feed per tooth (u_z), mm, formula (20 and 21) we get: u_z = 7,72 mm and u_z = 6,96 mm.

Table 3: Coordinates of the crest of kinematic waves

Radius of the teeth pair	$R_1 \ldots R_2$
Feed per tooth з (u_z), mm	0,75
Maximum reduced radius of the profile cutterhead, mm	53,3
Breduced radius of teeth: R_1, mm R_2, mm	 53,3 53,25
Imprecision in radii of the pair teeth, $\Delta i = R_1 - R_2$, mm	0,05
Serial number of the pair of teeth, i	1
Height of a crest of the kinematic waves (y) according by Eq. (17), mm	0,14
Abscissa (pitch) of the crest of the kinematic wave (x) by formula (15), mm	3,93

The inaccuracy in the cutter radius (Δ) must not exceed the height of the crest of kinematic waves (y), which is effective as shown in table 3.6. Furthermore, the feed per tooth (u_z) depend on two parameters: the first one is equal to the half of the maximum value of u_z at

$\Delta = 0$, and the second parameter is less than the first one by an error correction correcting (Δ) for the length of the radius.

CONCLUSION

The analyses done can be summarized in the following conclusions:

1. Inaccuracy in the cutter radius (Δ) must not exceed the height of the crest of kinematic waves (y). We strive to work with small depth of milling, as it reduces the cutting forces and the forces of pressure deforming the workpiece.

2. Feed per tooth (u_z) depends on two parameters: the first one is equal to the half of the maximum value of u_z at $\Delta = 0$, and the second parameter is less than the first one by error correction (Δ) for the length of the radius.

3. To match the height of the crest of kinematic waves of milled surface with given roughness, the following requirements should be met:

- To ensure concentricity of the cutter teeth, so that the error of their radii would not exceed the set values of roughness;
- It is essential to create the conditions for all cutter teeth to participate equally in the formation of surface milling. Concentricity of the cutting teeth is necessary for an accurate division in sharpening the tool. Therefore, leveling the radius of the teeth is periodically practiced by grinding with an abrasive disc.

4. In contemporary designs, and in particular in the specific universal profile cutterhead (Fig. 1), the knives are with fixing holes which are mounted to the fixing screws of the cutter body. Thus, the

concentricity of the cutting edges of the cutter is ensured. Difference in concentricity can occur in the process of grinding if breaking the sharpening technology.

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