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Značilnosti skobljanja lesa s poševno postavljenim valjastim vretenom in vpliv na površino

Characteristics of Wood Planing with an Obliquely Positioned Cylindrical Spindle and Its Effects on the Generated Surface

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Skobljanje lesa je po načinu obdelave obodno frezanje z valjastim vretenom. V lesni industriji spada med standardne postopke za obdelavo ravnih površin. Cilj pričujoče raziskave je bil raziskati značilnosti odrezavanja, ko teče podajanje obdelovanca poševno na os skobeljnega vretena. Prikazan je vpliv kota poševnosti skobeljnega vretena na geometrijsko obliko nastalega odrezka ter geometrijsko obliko nastale površine. Posebej je raziskan vpliv ekscentričnosti skobeljnega vretena na obliko obdelane površine. Izračunana geometrijska oblika površine je primerjana z izmerjeno površino po obdelavi dveh vrst lesa. Izmerjeni profili obdelane površine imajo močno izraženo periodičnost. V razmerah, v katerih je bila izvedena raziskava, določa z največjim vplivom valovno dolžino in amplitudo te periodičnosti pot rezalnih robov nožev skozi obdelovanec. Poleg te najvplivnejše frekvence določa obliko nastalega profila še naključni vpliv, ki je posledica anatomskih značilnosti strukture lesa.

Wood planing, by principle of operation, is circumferential contour milling with a cylindrical spindle. In the wood working industry, it is one of the conventional procedures for machining flat surfaces. The aim of this research was to study the characteristics of cutting when the feeding of the workpiece runs obliquely to the axis of the planing spindle. The research investigation studied the influence of the planing spindle angle of obliquity on the geometry of the generated surface and chip. Special attention was devoted to the effects of eccentricity of the planing spindle on the shape of the generated surface. The calculated geometry is compared to experimentally measured values after machining two different kinds of wood. The measured generated surface profiles have a strongly expressed periodicity. In the given machining conditions, the wave length and the amplitude of this periodicity are to a large extent defined by the path of the cutting edge through the workpiece. In addition to this most influential frequency, the shape of the generated profile is defined also by a random effect as a result of the anatomy characteristics of a given wood structure.

0 UVOD

Skobljanje lesa je po načinu obdelave obodno frezanje z valjastim vretenom. V lesni industriji spada med standardne postopke za obdelavo ravnih površin. Odrezovanje poteka z noži, ki so nameščeni po obodu skobeljnega vretena. Podajalno gibanje izvaja obdelovanec, ki se giblje pravokotno na vreteno. Odrezovalne hitrosti so razmeroma

0 INTRODUCTION

In terms of the principle of operation, wood planing is circumferential contour milling with a cylindrical spindle. In the wood working industry, it is among conventional procedures for machining flat surfaces. Cutting is performed by cutters placed along the circumference of the planing spindle. The cutting speeds achieved are relatively velike (do 60 m/s). Podajalne hitrosti lahko presegajo tudi vrednosti prek 100 m/min. Prednost postopka skobljanja je razmeroma majhna poraba energije, nezadostna pa je kakovost površine, ki jo je za zahtevne izdelke treba še brusiti.

Cilj pričujoče raziskave je bil raziskati značilnosti odrezovanja, ko teče podajanje obdelovanca poševno na os skobeljnega vretena.

high (upto 60 m/s), and the feed rates can exceed values of 100 m/min. The advantage of the planing process is a relatively low consumption of energy, but there is one disadvantage, i.e. that the machined surface quality is insufficient and grinding has to be applied.

The aim of this research investigation was to determine the characterstics of the planing procedure when the feeding of the workpiece runs obliquely to the planing spindle axis.

1 GIBANJE TOČKE NA KONICI NOŽA PRI SKOBLJANJU LESA S POŠEVNIM VRTEČIM SE VALJASTIM VRETENOM

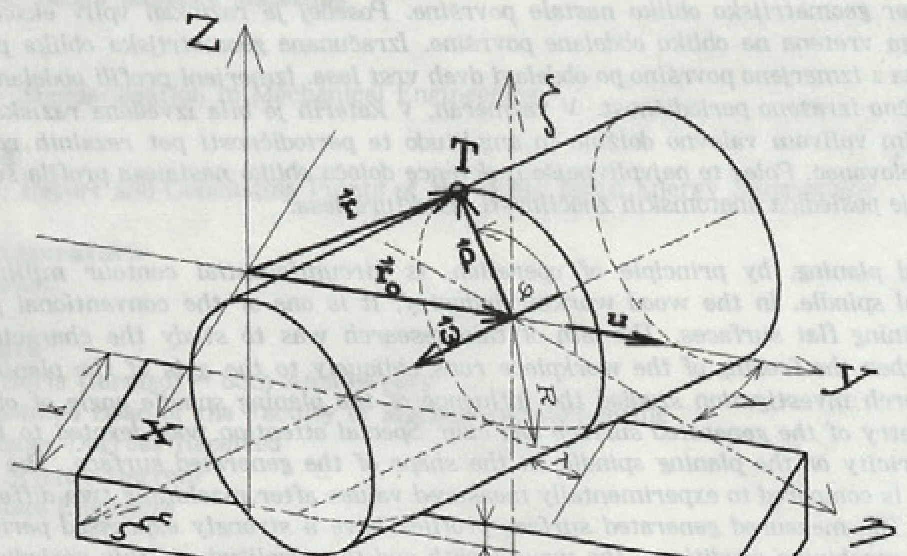
1.1 **Vektorski zapis poti točke na konici noža**

Pri poševno postavljenem skobeljnem vretenu točka na konici noža opisuje prostorsko gibanje. Izpeljane so enačbe takega gibanja in po tem določene značilnosti skobljanja s poševno postavljenim skobeljnim vretenom. Razmere so razvidne s slike 1, ki prikazuje poševno postavljeno skobeljno vreteno v koordinatnem sistemu in točko T na konici noža.

1 MOTION OF THE POINT ON THE CUTTER TIP IN WOOD PLANING WITH AN OBLIQUE ROTATING CYLINDRICAL SPINDLE

1.1 **Vector representation of the cutter tip point trajectory**

With an obliquely positioned planing spindle, the point on the cutter tip describes a curve in space. The contribution presents the equations describing this motion and on this basis defines the characteristics of the planing procedure with an obliquely positioned spindle. The conditions of the procedure can be seen from Fig.1, showing an obliquely placed planing spindle in the coordinate system and point T on the cutter tip, whose motion is defined.



Sl. 1. *Shema poševno postavljenega skobeljnega vretena v absolutnem in relativnem koordinatnem sistemu*

Fig. 1. *Obliquely positioned planing spindle in the absolute and relative coordinate systems*

Trenutna lega relativnega koordinatnega sistema (ξ, η, ζ) v absolutnem (x, y, z) določa vektor $\vec{r}_0$. Kot λ določa njegov zasuk okoli osi ζ. Določa torej kot λ, ki ga oklepa os skobeljnega vretena s pravokotnico na smer podajalne hitrosti.

The position of the relative coordinate system (ξ, η, ζ). in the absolute system (x, y, z) is defined by vector $\vec{r}$. The angle defines its turning motion around axis. In fact, it defines the angle between the planing spindle axis and a line perpendicular to

Orodje – skobeljno vreteno – se vrti v relativnem koordinatnem sistemu. Podajalno gibanje obdelovanca pomeni gibanje relativnega sistema v absolutnem koordinatnem sistemu. Hitrost tega gibanja je enaka podajalni hitrosti. Vektor $\vec{r}$ opisuje pot točke T na konici noža v absolutnem koordinatnem sistemu, vektor $\vec{\rho}$ pa v relativnem koordinatnem sistemu. Vektor $\vec{\omega}$ določa krožna frekvenco vretena okoli osi ξ v relativnem koordinatnem sistemu. Kot φ je zasuk vretena v odvisnosti od časa $\varphi = \omega_0 t$. Pri upoštevanju vektorja vrtilne frekvence $\vec{\omega}_0$, podajalne hitrosti u, polmera odrezovalnega kroga R in vektorja, ki določa gibanje relativnega koordinatnega sistema v absolutnem $\vec{r}_0$, sledi parametrična enačba za krajevni vektor $\vec{r}$, ki določa lego točke T v času t:

the direction of feed. The tool, i.e. the planing spindle, turns in the relative coordinate system. The feeding motion of the workpiece represents the motion of the relative system in the absolute coordinate system. The speed of this motion is equal to the feed rate. Vector $\vec{r}$ describes the path of point T on the cutter tip in the absolute coordinate system, white vector describes it in the relative coordinate system. The angle is the turning of the spindle in dependence on time and is $\varphi = \omega_0 t$. Considering the rotating speed vector $\vec{\omega}_0$, feed rate u, radius of the cutting circle R and the vector defining the motion of the relative coordinate system in the absolute system $\vec{r}_0$, we can write a parametric equation for the local vector $\vec{r}$ defining the position of point T in time t:

$$\vec{r} = R\cos(\omega_0\, t)\sin\lambda\, \vec{e}_1 + [\, u\, t + R\cos(\omega_0\, t)\cos\lambda]\, \vec{e}_2 + R\sin(\vec{\omega}_0\, t)\, \vec{e}_3 \qquad (1).$$

Podajalna hitrost u je glede na smer gibanja obdelovanca lahko pozitivna ali negativna. Rotacija točke na konici noža je pozitivna, če se vrti v nasprotni smeri od urnega kazalca.

Slika 2 prikazuje konstrukcijo trajektorije točke na konici noža poševnega skobeljnega vretena za protismerno podajanje, radij odrezovalnega kroga R = 60 mm, kot poševnosti vretena $\lambda = 30^\circ$ in če je pot, ki jo opravi obdelovanec v času enega vrtljaja 60 mm. Protismerno odrezovanje se pojavi, če je smer pomika odrezovalnega noža skozi obdelovanec v nasprotni smeri od podajalne smeri [1], [2]. Če poteka odrezovanje na spodnjem delu krivulje, je smer gibanja relativnega koordinatnega sistema v smer osi y pozitivna in rotacija točke na konici noža v ravnini (η, ζ) nasprotna od vrtenja urnega kazalca. Pot točke na konici noža T je na sliki 2 narisana tako, da je del krivulje za ravnino (y, z) narisan s tanjšo črto, del krivulje pred to ravnino pa z debelejšo črto.

Krivulja poti točke T je periodična, vendar pa pri kotu $\lambda > 0^\circ$ nima sečišč. Z določitvijo gibanja posamezne točke na konici noža je določena tudi pot ostrine noža, ki je vzporedna z osjo ξ skozi to točko. Geometrijska oblika odrezka in oblika površine po obdelavi sta določeni s potema dveh zaporednih odrezovalnih robov skozi obdelovanec.

Vektor $\vec{r}$ je mogoče zapisati tudi v poljubnem koordinatnem sistemu. Z zamenjavo enotskih vektorjev absolutnega sistema v enačbi (1), z enotskimi vektorji za kot λ zasukanega sistema okoli osi z, sledi:

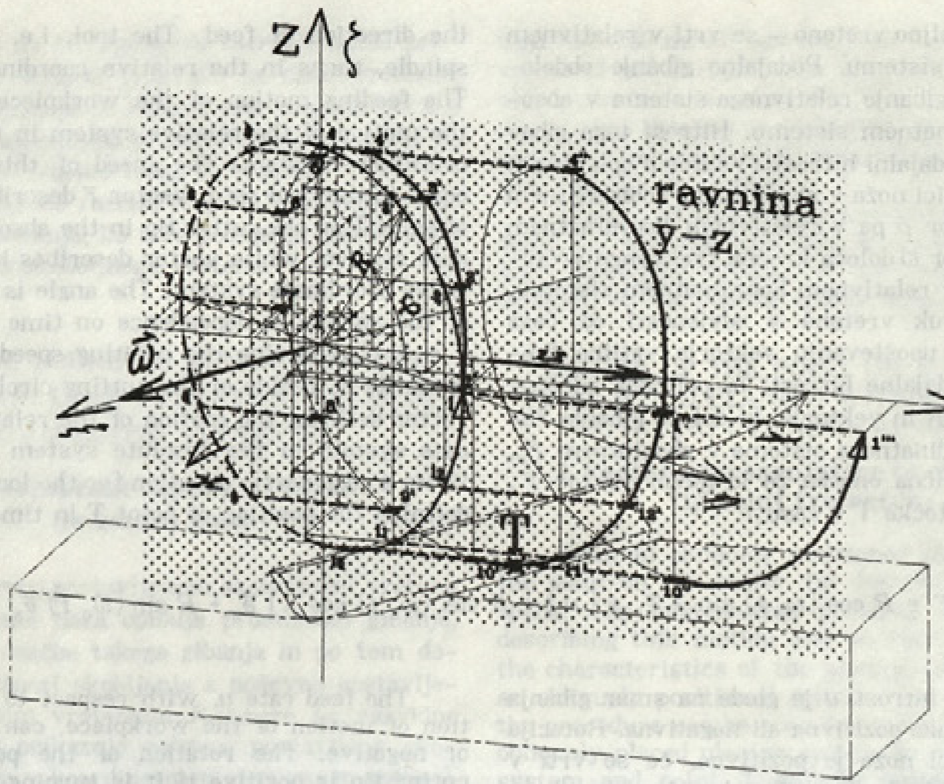
The feed rate u, with respect to the direction of motion of the workpiece, can be positive or negative. The rotation of the point on the cutter tip is positive if it is turning anti-clockwise.

Figure 2 shows the trajectory of the point on the cutter tip of an oblique planing spindle for up-feeding, a radius of the cutting circle R = 60 mm, an angle of inclination of the spindle $\lambda = 30^\circ$ if the path travelled by the workpiece in the time of one turn is 60 mm. By the term up-feeding, we understand a type of feeding in which the cutter moves through the workpiece in the direction opposite to the direction of feed, [1], [2]. If cutting is performed on the lower section of the curve, the direction of motion of the relative coordinate system in the y-axis direction is positive and the rotation of the point on the cutter tip in the plane (η, ζ) is anti-clockwise. The trajectory of the point on the cutter tip T is drawn in Figure 2 so that the part of the curve behind the (y, z) plane is presented by a thinner line and the part of the curve before this plane by a thicker line.

The curve of the path of point T is periodic. However, at angle $\lambda > 0^\circ$, there are no points of intersection on it. By defining the motion of a particular point on the cutter tip, we can define also path of the cutting edge of the cutter which runs parallel to the ξ axis through this point. The geometry of the chip and the shape of the surface after machining is defined by the paths of two sequential cutting edges through the workpiece.

Vector $\vec{r}$ can also be written in an arbitrary coordinate system. By replacing unit vectors in the absolute system in equation (1) by unit vectors for angle of the system turned round z-axis, we get:

$$\vec{r} = -\, u\, t\, \sin\lambda\, \vec{e}_1' + [\, u\, t\, \cos\lambda + R\cos(\omega_0\, t)]\, \vec{e}_2' + R\sin(\omega_0\, t)\, \vec{e}_3' \qquad (2).$$



Sl. 2. *Pot točke T na konici noža v absolutnem koordinatnem sistemu za protismerno odrezovanje*

Fig. 2 *Trajectory of point T on the cutter tip in the absolute coordinate system for upcutting*

V primeru, ko je kot zasuka vretena λ nič, preideta enačbi (1) in (2) v enačbo:

In a case in which the turning angle of the spindle λ is zero, equations (1) and (2) become:

$$\vec{r} = [\, u\,t + R\cos(\omega_0\, t)]\,\vec{e}_2 + R\sin(\vec{\omega}\,t)\,\vec{e}_3 \qquad (3),$$

ki je enačba podaljšane cikloide in je veljavna za standardni način skobljanja. Če primerjamo to enačbo z enačbo (2) vidimo, da je oblika dobljene krivulje v ravnini (y', z') ki je za kot λ zasukana okoli osi z, pri poljubnem kotu λ analogna tisti, ko je λ enak nič, saj komponenta v smeri x' ne vpliva na obliko odrezka in površine v tej ravnini. Upoštevati je treba le korekcijo za podajalno hitrost:

which is the equation of a lengthened cycloid and is valid for the conventional planing procedure. Comparing this equation to equation (2), we can see that the shape of the obtained curve in the plane (y', z') which is turned round z-axis by angle λ, at an arbitrary angle λ is analogue to that when λ is zero, since the component in the x' direction does not affect the shape of the chip and surface in this plane. All that is necessary to consider is the correction of the feed rate u:

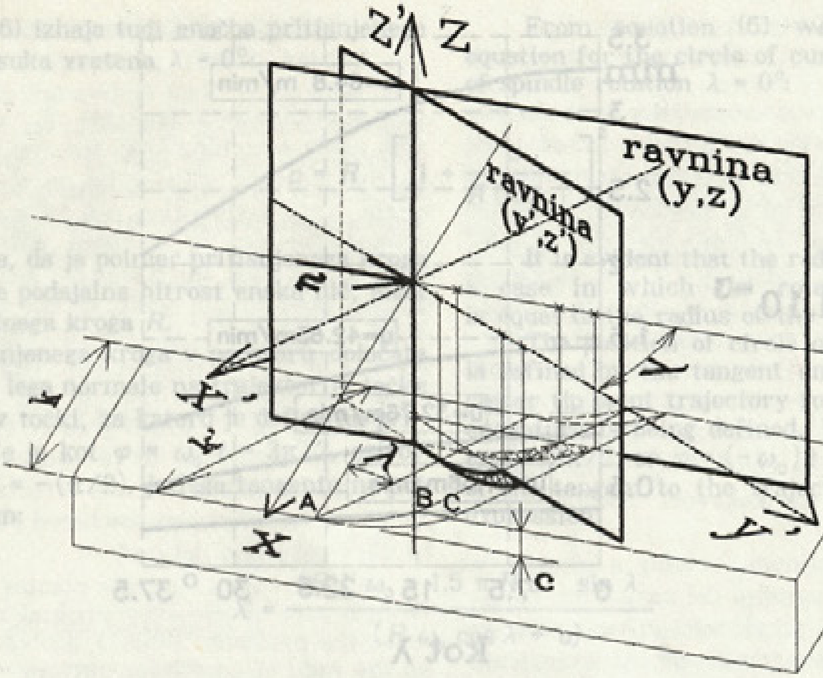
$$u_r = u\cos\lambda \qquad (4).$$

V ravnini (y', z') sta torej oblika odrezka in nastale površine določena z enačbo podaljšane cikloide. To v veliki meri poenostavlja preučevanje geometrijske oblike površine, nastale po odrezovanju, in študij geometrijske oblike odrezka.

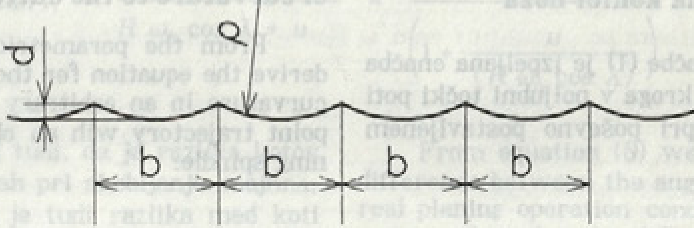
Geometrijsko obliko odrezka v ravnini (y', z') določata dve zaporedni podaljšani cikloidi, ki ju opišeta dva zaporedna noža in površina obdelovanca pred obdelavo, kakor prikazuje slika 3. Pri tem nastane valovita površina, ki je prikazana na sliki 4.

In the plane (y', z'), the shape of the chip and the created surface is thus defined by the equation of a lengthened cycloid. This greatly simplifies the study of surface geometry created by cutting and the study of the geometry of the chip.

The geometry of the chip in plane (y', z') is defined by two sequential lengthened cycloids which are described by two sequential cutters and by the surface of the workpiece before the procedure, as shown in Fig. 3. This generates the wavy surface presented in Fig. 4.



Sl. 3. *Geometrijska oblika odrezka v ravnini (y', z')*
Fig. 3. *Geometry of the chip in plane (y', z')*



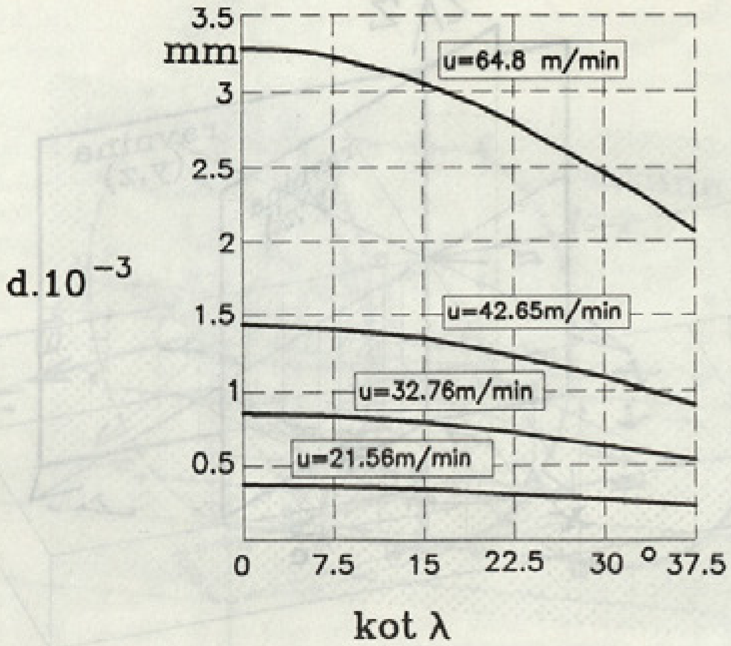
Sl. 4. *Oblika površine, nastale po skobljanju*
Fig. 4. *The shape of the surface generated by planing*

Po opisanih ugotovitvah je izračunana geometrijska oblika odrezovanja za naslednje razmere: radij odrezovalnega kroga R = 200 mm, število nožev na skobeljni glavi n_1 = 8, vrtilna frekvenca skobeljne glave n = 4 925 /min, podajalne hitrosti u = 21,56 ; 32,76 ; 42,65 in 64,8 m/min, kot poševnosti λ od nič do 37,5° in protismerno odrezovanje. Poševna postavitev skobeljnega vretena vpliva na geometrijsko obliko odrezka in geometrijsko obliko nastale površine. Slika 5 prikazuje dobljene rezultate za odvisnost višine vrha hrapavosti d od podajalne hitrosti in kota λ.

Vidimo, da daje poševno skobljanje možnosti za izboljšanje kakovosti površine, oziroma dopušča večje podajalne hitrosti za enako kakovost površine. To velja le za orodje, čigar ostrine nožev ležijo natančno na istem odrezovalnem krogu, kar je v praksi težko doseči.

On the basis of these findings, we can calculate the geometry of cutting for the following conditions: cutting circle radius R = 200 mm, the number of cutters on the head of a plane n_1 = 8, rotating speed of the head n = 4 925 rev/min, feed rate u = 21.56 ; 32.76 ; 42.65 and 64.8 m/min, angle of inclination λ from 0 to 37.5° all for up-cutting. The oblique position of the planing spindle has an effect on the geometry of the chip and the geometry of the created surface. Fig. 5 shows the obtained results for surface roughness peak height d depending on feed rate and angle λ.

We see that oblique planing offers the possibility of improving the surface quality or, in other words, it allows higher feed rates with the same surface quality. This holds only for a tool whose cutting edges it exactly in the same cutting circle, however which is difficult to achieve in practical operations.



Sl. 5. *Odvisnost višine vala hrapavosti d od podajalne hitrosti u in kota λ*

Fig. 5. *Roughness wave peaks d versus feed rate u and angle λ*

1.2 Določitev polmera pritisnjenega kroga poti točke na konici noža

Iz parametrične enačbe (1) je izpeljana enačba za polmer pritisnjenega kroga v poljubni točki poti točke na konici noža pri poševno postavljenem skobeljnem vretenu:

1.2 Determination of the radius of the circle of curvature to the cutter tip point trajectory

From the parametric equation (1) we can derive the equation for the radius of the circle of curvature in an arbitrary point of the cutter tip point trajectory wih an obliquely positioned planing spindle:

$$\rho = R \frac{\left[1 + \frac{u^2}{R^2 \omega_0^2} - \frac{2\, u}{R\, \omega_0} \sin(\omega_0\, t) \cos\lambda \right]^{\frac{3}{2}}}{\sqrt{1 + \frac{u^2}{R^2 \omega_0^2} - \frac{2\, u}{R\, \omega_0} \sin(\omega_0\, t) \cos\lambda - \frac{u^2}{R^2 \omega_0^2} \cos^2(\omega_0\, t) \cos^2\lambda}} \qquad (5).$$

Za raziskavo odrezovanja je za protismerno odrezovanje zanimiv polmer pritisnjenega kroga v točki, ki je določena s kotom $\varphi = \omega_0\, t = 3\pi/2$ in za istosmerno odrezovanje v točki $\varphi = (-\omega_0)\, t = -(\pi/2)$. V obeh primerih preide enačba (5) v:

For research in upcutting it is interesting to study the radius of curvature at the point which is defined by the angle $\varphi = \omega_0\, t = 3\pi/2$ and for down-cutting at the point $\varphi = (-\omega_0)\, t = -(\pi/2)$. In both cases equation (5) becomes:

$$\rho = R \left[1 + \frac{u^2}{R\, \omega_0} + \frac{2\, u}{R(\pm\omega_0)} \cos\lambda \right] \qquad (6).$$

Pozitiven predznak v imenovalcu drugega ulomka velja za protismerno, negativni pa za istosmerno odrezovanje.

The plus sign in the denominator of the second fraction holds for upcutting and the minus sign for down-cutting.

Iz enačbe (6) izhaja tudi enačba pritisnjenega kroga za kot zasuka vretena $\lambda = 0^0$:

From equation (6) we can get also the equation for the circle of curvature for the angle of spindle rotation $\lambda = 0^0$:

$$\rho = R\left[1 + \frac{u}{R(\pm\omega_0)}\right]^2 \qquad (7).$$

Razvidno je, da je polmer pritisnjenega kroga v primeru, ko je podajalna hitrost enaka nič, enak radiju odrezovalnega kroga R.

Lego pritisnjenega kroga v prostoru določata lega tangente in lega normale na trajektorijo točke na konici noža v točki, za katero je definiran pritisnjeni krog. Če je kot $\varphi = \omega_0 t = 3\pi/2$, oziroma $\varphi = (-\omega_0)t = -(\pi/2)$, je lega tangente na pot podana z zapisom:

It is evident that the radius of curvature, in a case in which the rotating speed is zero, is equal to the radius of the cutting circle R.

The position of circle of curvature in space is defined by the tangent and the normal to the cutter tip point trajectory for which the circle of curvature is being defined. When the angle $\varphi = \omega_0 t = 3\pi/2$, or $\varphi = (-\omega_0)t = -\pi/2$, the position of the tangent to the trajectory is given by the expression:

$$X = \frac{(R\,Y\,\omega_0 - 1{,}5\,\pi R\,u)\ \sin\lambda}{(R\,\omega_0\cos\lambda + u)}$$

Iz te enačbe izhaja, da je kot λ' med smerjo osi y in tangento na pot v opazovani točki, določen z enačbo:

From the equation, it follows that angle λ' between the y-axis and the tangent to the trajectory in the observed point is defined by:

$$\tan\lambda' = \frac{R\,\omega_0\,\sin\lambda}{R\,\omega_0\cos\lambda + u} = \frac{\tan\lambda}{\left(1 + \dfrac{u}{(R\,\omega_0\cos\lambda)}\right)} \qquad (8).$$

Iz enačbe (8) izhaja tudi, da je razlika kotov $\lambda - \lambda'$ v realnih razmerah pri skobljanju majhna. To upravičuje sklep, da je tudi razlika med koti klina orodja v pravokotni in prečni ravnini (smer rezanja) zanemarljiva.

Lega normale v obravnavani točki je določena s koordinatama: $X = 0$ in $Y = (3\pi u)/2\omega$ ter je vzporedna z osjo z.

Krivulje točke T na ostrini noža v področju odrezovanja, lahko zelo natančno aproksimiramo s pritisnjenim krogom. Celoten proces odrezovanja je torej mogoče ponazoriti z nizom pritisnjenih krogov, ki si sledijo v smeri podajalne hitrosti z enakomernimi presledki:

From equation (8) we can also see that the difference between the angles $\lambda - \lambda'$ is small in real planing operation conditions. This allows to assume that also the difference between the angles of the wedge of the tool in orthogonal and tangential plane (direction of cutting) is negligible.

The normal position at the discussed point is defined by the coordinates: $X = 0$ and $Y = (3\pi u)/2\omega$ and is parallel to the z-axis.

The curve of the path of point T on the cutting edge in the cutting zone can be very accurately approximated by the circle of curvature. The whole process of cutting can thus be presented by a series of circles of curvature following each other in the direction of feed rate in equal spacings:

$$b = u\,t = \frac{2\,\pi\,u}{\omega_0\,n_l},$$

pri čemer je n_l število nožev v skobeljnem vretenu.

S polmerom pritisnjenega kroga je oblika obdelovane površine dovolj natančno določena. Ker je ta pri protismernem odrezovanju večji kakor pri istosmernem, je tudi višina hrapavosti obdelane površine pri protismernem odrezovanju manjša, kakor pri istosmernem.

where n_l is number of cutters on planing spindle.

The shape of the generated surface is defined accurately enough by the radius of the circle of curvature. Since this radius is larger in upcutting than in down-cutting, the height of the roughness peaks of the machined surface in upcutting is smaller than in down-cutting.

2 VPLIV IZSREDNOSTI VRETENA NA GEOMETRIJSKO OBLIKO OBDELANE POVRŠINE

Analizirana je bila geometrijska oblika odrezovanja ob predpostavki, da ležijo polmeri vseh nožev na delovnem vretenu na istem odrezovalnem krogu. Tej predpostavki se je mogoče približati le, če je skobeljni stroj opremljen z napravo za priostrovanje. Zaradi izsredne pritrditve skobeljne glave na gred ali zaradi večje ali manjše izsrednosti pogonske gredi, je neka izsrednost skobeljnega orodja zelo pogosta. Valovitost površine zaradi izsrednosti je lahko precej večja od hrapavosti površine, ki nastane po obdelavi s centričnim vretenom. Zato je treba določiti vpliv izsrednosti skobeljnega vretena na kakovost obdelane površine.

Meritve na skobeljnem vretenu, s katerim je bil opravljen eksperimentalni del raziskave, ponazarjajo ta problem. V preglednici 1, so prikazani odstopki polmerov posameznih nožev, izmerjenih po ostrenju na stroju za ostrenje in odstopki, izmerjeni po montaži skobeljnega vretena na gred stroja.

2 EFFECTS OF SPINDLE ECCENTRICITY ON MACHINED SURFACE GEOMETRY

A preliminary analysis of cutting geometry was made assuming that the radii of all cutters on the working spindle lie on the same cutting circle. This assumption can be made only if the planing machine is equipped with a sharpening device. Because of eccentric placement of the planing head on the shaft, or due to more or less large eccentricity of the driving shaft, some amount of eccentricity of the planing tool is very often the case. Waviness of the surface due to eccentricity can be much greater than the surface roughness generated by a centric spindle. It is therefore necessary for the effects of the planing spindle eccentricity on machined surface quality to be very carefully defined.

Measurements on the planing spindle which were a part of the experimental research, illustrate the problem. Table 1 shows the deviations on the radii of particular cutters, measured after sharpening on the sharpening machine, and the deviations measured after mounting the spindle on the planing machine shaft.

Preglednica 1: *Odstopek polmerov po ostrenju in montaži*
Table 1: *Radii deviations after sharpening and mounting*

Odstopek polmera po ostrenju v mm — Radius deviation after sharpening in mm									
nož številka	1	2	3	4	5	6	7	8	cutter No
prvo ostrenje	0.000	0.002	0.001	0.004	0.003	0.001	0.003	0.002	first sharpening
drugo ostrenje	0.002	0.004	0.003	0.004	0.000	0.002	0.002	0.001	second sharpening
Odstopek polmera po montaži v mm — Radius deviation after mounting in mm									
prvo ostrenje	0.031	0.041	0.033	0.021	0.010	0.000	0.090	0.016	first sharpening
drugo ostrenje	0.000	0.010	0.017	0.030	0.040	0.031	0.022	0.009	second sharpening

Iz primerjave vrednosti meritev po ostrenju in po montaži izhaja, da je os orodja nasproti rotacijski osi na skobeljnem stroju premaknjena za 0,02 mm. Odstopki polmerov odrezovalnih krogov po montaži zaradi izsrednosti gredi so približno desetkrat večji od odstopkov po ostrenju. Zato je za primerjavo profila teoretično izračunane površine z dejansko odrezano površino nujno treba upoštevati še vpliv izsrednosti.

Vpliv izsrednosti skobeljnega vretena na obliko obdelane površine lahko določimo, če opredelimo pot posameznih noževih ostrin. Pri tem je polmer odrezovalnega kroga posameznega noža R_i glede na rotacijsko os določen z enačbo:

A comparison of the measured values after sharpening and after mounting shows that with respect to the axis of rotation of the planing machine, the tool axis is misaligned by 0.02 mm. The deviations of the cutting circle radii after mounting due to shaft eccentricity are approximately ten times greater than after sharpening. Hence, to compare the profile of the theoretically calculated surface with the real surface, the effects of eccentricity have to be considered.

The effects of eccentricity of the planing spindle on the shape of the machined surface can be defined if we define the paths of particular cutting edges. The cutting circle radius of a particular cutter R_i with respect to the axis of rotation, is defined by the equation:

$$R_i = R\left[1 + e\sin\left(\frac{2\pi i}{n_i}\right)\right] \quad (9),$$

kjer pomenijo: e — izsrednost skobeljnega vretena, n_i — število nožev na skobeljnem vretenu in i — zaporedno številko noža, i = 1 do n_i.

where: e — eccentricity of the planing spindle, n_i — number of cutters on the planing spindle, and i — sequential number of the cutter, i = 1 to n_i.

Površino pri skobljanju oblikujejo noži z različnimi polmeri. Hrapavost površine določajo sečišča posameznih zaporednih poti. Pri analizi tega problema za poševno skobljanje zadošča opazovanje gibanja orodja samo v ravnini (y', z') ob upoštevanju korigirane podajalne hitrosti. Ker je za geometrijsko obliko novo nastale površine zanimiv le zelo majhen segment podaljšane cikloide v območju točke, ko posamezen nož doseže kot $\varphi = \omega_0 t = 3\pi/2$, je mogoče z zelo veliko natančnostjo krivuljo podaljšane cikloide v tem območju nadomestiti s segemntom pritisnjenega kroga. Iz enačbe (7) izhaja, da je polmer pritisnjenega kroga v tej točki:

In planing, the surface is generated by cutters of different radii. Surface roughness is defined by the points of intersection between sequential trajectories. In the analysis of this problem for oblique planing, it suffices to observe the motion of the tool only in the plane (y', z') bearing in mind the corrected feed speed. Since for the geometry of the newly generated surface we are interested only in a very small segment of the lengthened cycloid in the area of the point when a particular cutter reaches the angle $\varphi = \omega_0 t = 3\pi/2$, it is possible, with very great accuracy, to replace the curve of the lengthened cycloid in this area by a segment of the circle of curvature. From equation (7) we see that the radius of the circle of curvature in this point is :

$$\rho_{0i} = R_i \left(1 + \frac{u}{R_i\ \omega_0}\right)^2$$

Koordinate središč teh krogov so: v smeri osi z:

The coordinates of the centre points of these circles are: In the direction of z-axis:

$$z_{0,i} = -R + \rho_{0,i} = -R_i + R_i\left(1 + \frac{u}{R\ \omega_0}\right)^2 = \frac{2\ u}{\omega_0} + \frac{u^2}{R_i\ \omega_0^2} = 2\,a + \frac{a^2}{R_i},$$

kjer je a kotalni krog podaljšane cikloide:

where a — rolling circle of the lengthened cycloid:

$$a = u/\omega_0$$

in v smeri osi y:

In the direction of y-axis:

$$y_{0,i} = \frac{2\pi\, i\ u}{\omega_0\ n_i} = \frac{2\pi\, i\ a}{n_i} = b\ i$$

$i = 1, 2, 3 \ldots\ldots, n_i, n_i + 1$, pri čemer je i zaporedno število noža.

Tako definirani pritisnjeni krogi določajo geometrijsko obliko nastale površine po skobljanju z izsrednim vretenom. Analiza mora zajeti vsaj en poln obrat vretena.

Po teh ugotovitvah je bil izdelan numerični program za izračun profila novo nastale površine na segmentu enega polnega obrata delovnega vretena. Nastala površina je sestavljena iz krožnih lokov s polmerom $\rho_{0,i}$, kakor prikazuje slika 6. Zaradi boljše preglednosti je razmerje med osjo y in osjo z močno povečano.

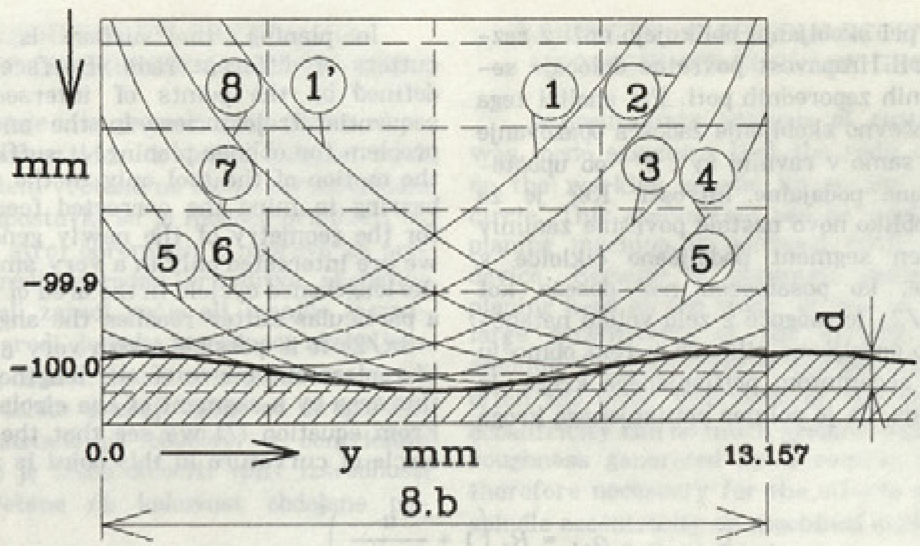
Najvišjo točko na opazovanem profilu določa sečišče noža številka 1 in 2, oziroma 8 in 1', najnižjo točko pa oblikuje nož številka 5 na sredini vala. Višino vala neravnosti dobljene površine določa razlika med najvišjo in najnižjo točko in v tem primeru znaša d = 0,0408 mm. Razviden je velik vpliv izsrednosti vretena na višino vala neravnosti obdelane površine. Višina nastalega vala

$i = 1, 2, 3 \ldots\ldots, n_i, n_i + 1$ where i is the sequential number of the cutter.

The thus defined circles of curvature define the geometry of the surface generated by planing with an eccentric spindle. The analysis has to include at least one full revolution of the spindle.

On the basis of these findings, we designed a numerical program for calculating the profile of the newly generated surface on a segment of one full revolution of the working spindle. The generated surface consists of circular arcs with a radius $\rho_{0,i}$ as shown in Fig. 6. For reasons of better clarity, the relation between y and z-axes is strongly enlarged.

The highest point on the observed profile is determined by the point of intersection of cutters number 1 and 2, or 8 and 1', and the lowest point is formed by the cutter number 5 in the middle of the wave. The height of the unevenness wave of the obtained surface is determined by the difference between the highest and lowest point and in this case amounts to d = 0.0408 mm. The large influence of the eccentricity of the spindle on the height of the unevenness wave of the machined



Sl. 6. *Oblika površine za primer: podajalna hitrost u = 64,8 m/min, polmer odrezovalnega kroga R = 100 mm, število nožev na skobeljnem vretenu n_j = 8, vrtilna frekvenca vretena n = 4925/min, kot poševnosti vretena λ = 0 in izsrednost vretena e = 0,02 mm.*

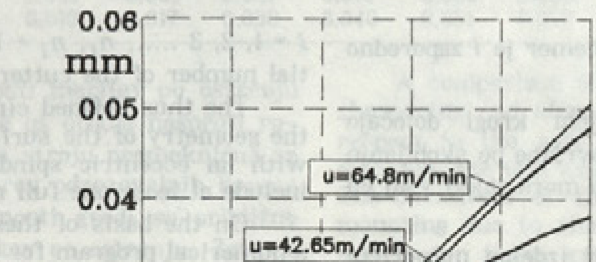
Fig. 6. *The shape of the surface for the case: feed rate u = 64.8 m/min, radius of the cutting circle R = 100 mm, number of cutters on the planing spindle n_j = 8, rotating speed of the spindle n = 4925/min, angle of spindle inclination λ = 0 and spindle eccentricity e = 0.02 mm.*

pri takem izsrednem vretenu je v primerjavi s centričnim vretenom več ko 10-krat večja.

Višina vala profila je odvisna, pri sicer enakih razmerah, tudi od podajalne hitrosti. Ta vpliv je za različne izsrednosti in podajalne hitrosti, pri kotu poševnosti vretena $\lambda = 0^0$, prikazan na sliki 7.

surface can be observed. The height of the created wave at the given spindle eccentricity is more than 10-times greater than the centric spindle.

The height of the wave depends, in otherwise equal conditions, also on the feed rate. This effect for different eccentricities and feed rates, at an angle of inclination of the spindle $\lambda = 0^0$, is shown in Fig. 7.



Sl. 7. *Vpliv izsrednosti gredi in podajalne hitrosti na višino vala neravnosti λ = 0*

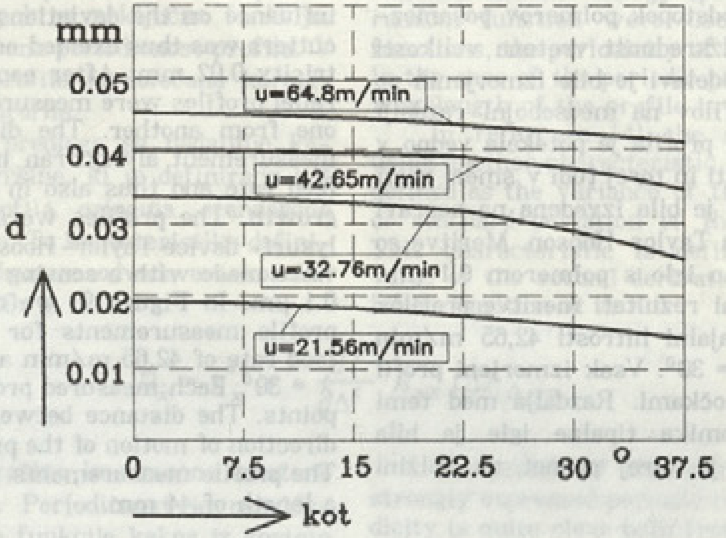
Fig. 7. *The effects of shaft eccentricity and feed rate on the height of unevennes wave, λ = 0*

Zelo karakterističen je prelom krivulje za podajalno hitrost 21,56 m/min pri izsrednosti skobeljnega vretena med 0,005 in 0,01 mm. Analiza nastale površine v območju izsrednosti med 0,005 in 0,01 mm za krivuljo za podajalno hitrost 21,56 m/min pokaže, da v tem območju izdelajo površino samo trije noži.

Slika 8 prikazuje vpliv kota poševnosti skobeljnega vretena λ na višino vala neravnosti d pri izsrednosti skobeljnega vretena $e = 0{,}02$ mm. Drugi parametri na tej sliki so enaki kakor v prejšnjem primeru. Sklenemo lahko, da je pri izsrednem skobeljnem vretenu vpliv kota poševnosti na izboljšanje kakovosti površine manjši kakor pri centričnem vretenu.

The turning of the curve for the feed rate 21.56 m/min at a spindle eccentricity ranging between 0.005 and 0.01 mm is very characteristic. The analysis of the generated surface in an eccentricity range between 0.005 and 0.01 mm for a feed rate 21.56 m/min shows that, in this range, the surface is made made by only three cutters.

Figure 8 shows the effects of an angle of the planing spindle obliquity λ on the height of unevenness wave d at a spindle eccentricity $e = 0.02$ mm. All other parameters in this figure are the same as in the previous case. It is possible to conclude that, with an eccentric planing spindle, the effect of the angle of obliquity on the improvement of surface quality is smaller than with a centric spindle.



Sl. 8. *Vpliv kota poševnosti na največjo višino profila, e = 0,02 mm*

Fig. 8. *The effects of the angle of inclination on the maximum profile height, e = 0.02 mm*

3 DEJANSKA POVRŠINA PO SKOBLJANJU S POŠEVNIM SKOBELJNIM VRETENOM

S študijem kinematike orodja, torej z določitvijo poti rezalnih nožev skozi obdelovanec, je določen teoretični profil površine, nastale po obdelavi.

Anizotropnost in nehomogenost sta dve značilnosti lesa, ki določata način porušitve lesnega tkiva ob konici noža. Zato profil dejanske površine po odrezovanju odstopa od teoretičnega. Za določitev karakteristik dejanskega profila površine, nastalega po obdelavi lesa, je bila izvedena vrsta meritev. Izmerjeni rezultati so bili primerjani z izračunanimi.

Analiza dejanske površine, ki nastane po obdelavi lesa, je bila izvedena na dveh obdelovancih, in sicer iz bukovega in smrekovega lesa. Za vsako vrsto lesa je bil izbran en obdelovanec brez večjih napak v rasti (grče in podobno). Tako je bila iz

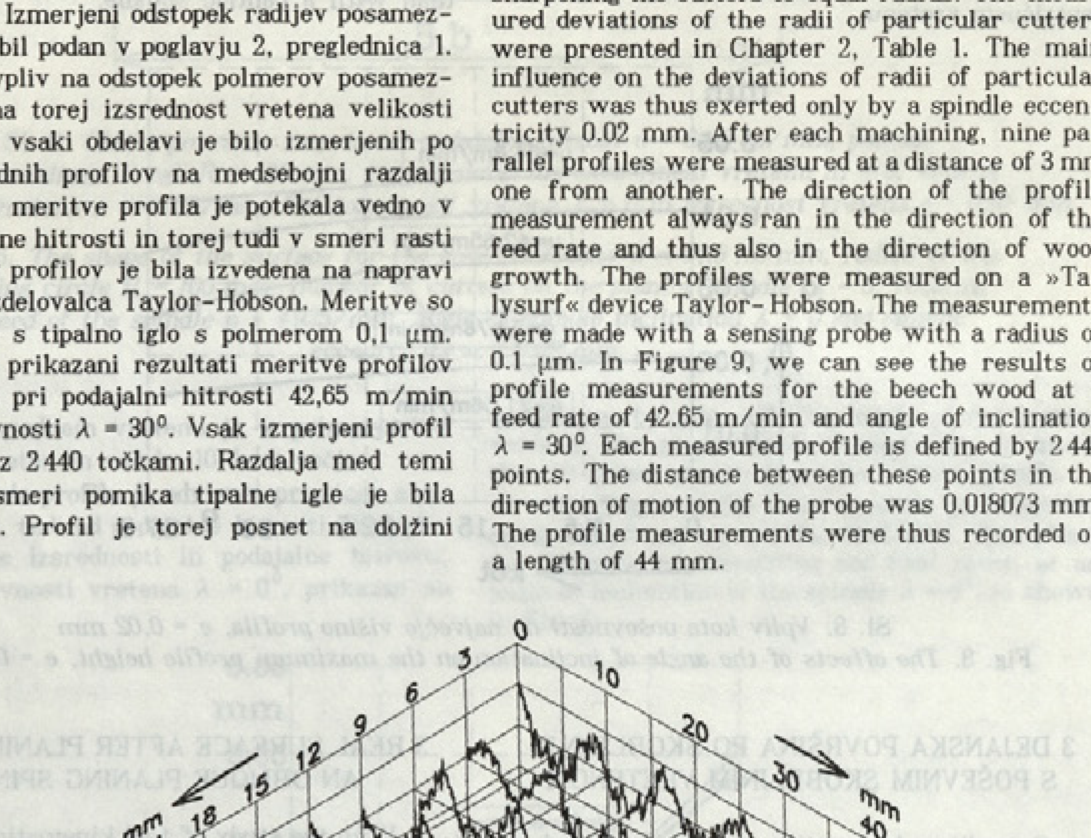
3 REAL SURFACE AFTER PLANING WITH AN OBLIQUE PLANING SPINDLE

With the study of tool kinematics, that is by determining the paths of cutters through the workpiece, we can define the theoretical profile of the surface generated in machining.

Anisotropy and non-homogeneity are two characteristics of wood which define the way in which the wood tissue at the cutter tip will fracture. For this reason, the real surface profile after cutting differs from the theoretical one. In order to determine the characteristics of the real surface profile after cutting, a number of measurements were made, and the measured results were compared with the calculated results.

The analysis of the real surface generated after the wood working operation was made on two workpieces, one from beech and one from pinewood. Each type of wood was represented by one workpiece having no major flaws in growth (knots and similar). In this way, the analysis ocene v največji mogoči meri izključena variacija lastnosti iste vrste lesa, ki je posledica različnih pogojev rasti posameznega drevesa. Obdelovalna površina je bila izbrana tako, da je bil rez izveden vzdolž vzdolžne smeri v radialni ravnini. Izmerjena vlaga vzorca iz bukovega lesa je bila 19 %, vzorca iz smrekovega lesa pa 18 %. Oba obdelovanca sta bila obdelana pri dveh različnih podajalnih hitrostih in dveh različnih kotih poševnosti skobeljnega vretena. Prosti kot rezalnega klina α je bil 20°, kot klina β 43°, cepilni kot γ pa 27°. Pred izvedbo meritve je bilo orodje na novo priostreno na industrijskem stroju za ostrenje. Stroj ni bil opremljen z napravo za priostrovanje nožev na enak polmer. Izmerjeni odstopek radijev posameznih nožev je bil podan v poglavju 2, preglednica 1. Prevladujoč vpliv na odstopek polmerov posameznih nožev ima torej izsrednost vretena velikosti 0,02 mm. Po vsaki obdelavi je bilo izmerjenih po devet vzporednih profilov na medsebojni razdalji 3 mm. Smer meritve profila je potekala vedno v smeri podajalne hitrosti in torej tudi v smeri rasti lesa. Meritev profilov je bila izvedena na napravi »Talysurf« izdelovalca Taylor-Hobson. Meritve so bile izvedene s tipalno iglo s polmerom 0,1 µm. Na sliki 9 so prikazani rezultati meritve profilov za bukov les pri podajalni hitrosti 42,65 m/min in kotu poševnosti λ = 30°. Vsak izmerjeni profil je definiran z 2 440 točkami. Razdalja med temi točkami v smeri pomika tipalne igle je bila 0,018073 mm. Profil je torej posnet na dolžini 44 mm.

excluded, to the highest possible extent the variation in properties in the same kind of wood resulting from different growth conditions of a particular tree. The surface to be machined was chosen so that the cut was made in the longitudinal direction in the radial plane. The moisture content in the beech workpiece was 19% and in the pinewood workpiece 18%. Both workpieces were machined at two different feed rates and two different angles of inclination of the planing spindle. The clearance angle of the cutting wedge α was 20°, the wedge angle β 43° and the rake angle γ 27°. Prior to measurements the tool was resharpened on an industrial dressing machine. The machine was not equipped with a device for resharpening the cutters to equal radius. The measured deviations of the radii of particular cutters were presented in Chapter 2, Table 1. The main influence on the deviations of radii of particular cutters was thus exerted only by a spindle eccentricity 0.02 mm. After each machining, nine parallel profiles were measured at a distance of 3 mm one from another. The direction of the profile measurement always ran in the direction of the feed rate and thus also in the direction of wood growth. The profiles were measured on a »Talysurf« device Taylor-Hobson. The measurements were made with a sensing probe with a radius of 0.1 µm. In Figure 9, we can see the results of profile measurements for the beech wood at a feed rate of 42.65 m/min and angle of inclination λ = 30°. Each measured profile is defined by 2 440 points. The distance between these points in the direction of motion of the probe was 0.018073 mm. The profile measurements were thus recorded on a length of 44 mm.



Sl. 9. *Površina obdelovanca iz bukovega lesa pri podajalni hitrosti 42.65 m/min in kotu poševnosti λ = 30°*

Fig. 9. *Beech wood workpiece surface at feed rate 42.65 m/min and angle of inclination λ = 30°*

Smer porušitve lesnega tkiva ob konici noža je zaradi specifične anizotropnosti in nehomogenosti lesnega tkiva naključna. Vpliv naključne komponente na nastali profil je znaten. Za analizo topografskih značilnosti tako nastale površine so primerne statistične metode za analizo naključnih procesov [3] do [5].

Profil obdelane površine je naključna ustaljena funkcija. Tako funkcijo opisujejo v smeri ordinate znane statistične karakteristike [3]: srednja vrednost, aritmetično standardno odstopanje, raztros, poševnost gostote porazdelitvene funkcije in sploščenost gostote porazdelitvene funkcije.

Za vrednotenje naključne funkcije v smeri abscise sta uporabljeni avtokorelacijska funkcija in gostota energijskega spektra naključne funkcije. Iz teh funkcij je definirana periodičnost profila. V primeru periodičnega profila je določena korelacijska valovna dolžina profila.

V viru [4] avtor predlaga še nadaljnjo karakteristiko profila površine, ki je definirana kot raztros poševnosti profila oziroma standardno odstopanje nagiba profila. To karakteristiko definira negativna vrednost drugega odvoda avtokorelacijske funkcije pri $\Delta = 0$:

The direction of fracture of wood tissue at the cutter tip is due to anisotropy and non-homogeneity of the wood tissue of random character. The influence of the random component of the generated profile is considerable. In order to analyse the topographical characteristics of the surface thus created, reference can be made to statistical methods for the analysis of random processes [3] to [5].

The profile of the machined surface is a random stationary function. This kind of function is described in the direction of the ordinate by known statistical characteristics [3]: mean value, arithmetic standard deviation, variance, inclination of the density distribution function and flattening of the density distribution function.

For the evaluation of the random function in the direction of the abscissa, the autocorrelation function and the energy spectrum density of the random function were used. From these two functions, the periodicity of the profile is defined. In the case of the periodic profile, the correlative wavelength of the profile is defined.

In reference [4] the author also suggests using another characteristic of the surface profile defined as the variance of the profile inclination, or standard deviation of the profile inclination. This characteristic is defined by the negative value of the second derivative of the autocorrelation function at $\Delta = 0$:

$$D_{\dot{x}} = \sigma_{\dot{x}}^2 = -\frac{d^2}{d\Delta^2} R_{xx}(\Delta)\Big|_{\Delta=0}$$

Profil obdelane površine ima močno izraženo periodično komponento. Periodičnost je razvidna tako iz avtokorelacijske funkcije kakor iz gostote energijskega spektra. Frekvenca oziroma valovna dolžina nosilnega vala profila se ujema z izračunanimi karakteristikami teoretično določenega profila. Pri pogojih, pri katerih je bila opravljena raziskava, določa valovno dolžino in amplitudo te periodičnosti z največjim vplivom pot rezalnih robov posameznih nožev skozi obdelovanec. Poleg te najvplivnejše frekvence določa obliko nastalega profila še naključni vpliv, ki je posledica anatomskih značilnosti strukture lesa.

V viru [5] avtor sistematizira značilnosti profila površine, nastale po obdelavi, v pet tipičnih skupin. V razmerah, v katerih je bila opravljena ta raziskava, spadajo izmerjeni profili površine, nastale po skobljanju lesa po tej klasifikaciji, v drugo skupino.

Izvedene so bile tudi meritve profilov površine, nastale po obdelavi plastične mase »koterm«, in sicer v enakih razmerah, v katerih so bili obdelani obdelovanci iz bukovega in smrekovega lesa. Visoka stopnja korelacije med izmerjenim profilom, nastalim po obdelavi koterma in izračunanim profilom, dovoljuje sklep, da je vpliv naključne komponente na profil površine relativno

The profile of the machined surface has a strongly expressed periodic component. The periodicity is quite clear both from the autocorrelation function and from the energy spectrum density. The frequency or the wave length of the main profile wave correlates with the calculated characteristics of the theoretically calculated profile. In the conditions in which the investigations were made, the wave length and the amplitude of this periodicity with the greatest influence, were defined by the cutting edge paths of particular cutters through the workpiece. In addition to this most influential frequency, the shape of the newly generated profile is also affected by another influence of random character resulting from the anatomy characteristics of wood structure.

In reference [5] the author systemizes the characteristics of the surface profile generated after machining in five typical groups. In the conditions in which this research investigation was made, the profiles of the surface that were measured after the planing operation belong to the second group.

Measurements were also made of surface profiles generated after machining a plastic material cotherm, in the same conditions as for planing beech and pinewood workpieces. A high degree of correlation between the measured profile generated after planing cotherm and the calculated profile allows to conclude that the influence manjši kakor pri obdelavi lesa. Primerjava profila, nastalega po obdelavi koterma s profilom, nastalim po obdelavi lesa rabi za oceno vpliva naključne komponente na profil.

Iz primerjave izračunanih vrednosti za koterm in les je razvidno, da se pojavi največja razlika med posameznimi profili pri karakteristiki, ki jo definira standardno odstopanje nagiba profila. Standardno odstopanje nagiba profila pri obdelovancu iz koterma je za 2 do 4-krat manjša kakor pri obeh vrstah lesa. Standardno odstopanje nagiba profila torej definira vpliv naključne komponente na profil površine.

Razlika med standardnim odstopanjem nagiba profila pri kotu poševnosti skobeljnega vretena 0^0 do 30^0 je pomembna pri podajalni hitrosti 22,56 m/min, pri podajalni hitrosti 42,65 m/min pa ne. Valovna dolžina in amplituda determinističnega dela nosilnega vala sta pri večji podajalni hitrosti večja, torej je njun relativen vpliv na profil površine večji, delež naključne komponente pa relativno manjši. Vrednosti za standardno odstopanje nagiba so za obe vrsti lesa večje pri kotu poševnosti skobeljnega vretena $\lambda = 30^\circ$. Podobno je vidno tudi pri obdelavi koterma.

Razlika med standardnim odstopanjem nagiba profila med obema vrstama lesa je pomembna, razen v primeru podajalne hitrosti 42,65 m/min in kotu $\lambda = 0^\circ$. Anatomske značilnosti posamezne vrste lesa torej vplivajo na karakteristike profila površine nastalega po obdelavi. Vrednosti za standardno odstopanje poševnosti za bukov les so višje kakor pri smrekovem lesu.

Le pri obdelovancu iz bukovega lesa pri podajalni hitrosti 42,65 m/min je razvidna pomembna razlika za srednje odstopanje profila R_a. V preostalih treh primerjavah ni mogoče dokazati vpliva na srednje odstopanje profila R_a in s tem izboljšanja kakovosti površine pri skobljanju s poševno postavljenim skobeljnim vretenom. Razlog za to je povečan vpliv naključne komponente pri poševno postavljenem skobeljnem vretenu na obliko profila.

4 SKLEPI

Točka na konici noža poševno postavljenega skobeljnega vretena opisuje prostorsko krivuljo, za katero je podana enačba v parametrični obliki. S to enačbo je določena oblika površine po obdelavi. Pot točke na konici noža je mogoče zelo natančno opisati v področju odrezovanja tudi s pritisnjenim krogom.

of the random component on the surface profile is relatively smaller than in the case of machining wood. A comparison of the cotherm profile to that of wood can thus be used to assess the influence of the random component on the profile.

From the comparison of the calculated values for cotherm and wood it is clear that the biggest difference between the particular profiles appears at a characteristic defined as standard deviation of the profile inclination. The standard deviation of the profile deviation on a cotherm workpiece is smaller than in both kinds of wood by a factor of 2 to 4. The standard profile inclination deviation thus defines the influence of the random component on the surface profile.

The difference between the standard deviation of the profile inclination at a planing spindle angle of inclination from 0° to 30° is significant at a feed rate 22.56 m/min whereas at a feed rate 42.65 m/min, it is not. The wave length and the amplitude of the deterministic part of the dominant wave are greater at a higher feed rate, so their relative influence on the surface profile is bigger, and the share of the random component is relatively smaller. The values of the standard deviation of inclination are bigger at a planing spindle angle of inclination $\lambda = 30^0$ for both kinds of wood. A similar conclusion can also be made in machining cotherm.

The difference between the profile inclination standard deviation of the two kinds of wood is significant, except at a feed rate of 42.65 m/min and angle $\lambda = 0^\circ$. This means that the anatomy characteristics of a particular kind of wood have a certain effect on the characteristics of the surface profile generated by machining. The standard deviation values of inclination are higher for the beech wood than for the pinewood.

Only at the workpiece from beech wood at a feed rate 42.65 m/min is there a significant difference in the mean deviation of profile R_a. In the other three comparisons, it is not possible to prove any influence on the mean deviation of profile R_a and improvement of surface quality after planing with an obliquely positioned spindle. The reason for this is an increased effect of the random component on the shape of profile.

4 CONCLUSIONS

The point on the cutter tip of an obliquely positioned planing spindle describes a curve in space for which the equation is given in a parametric form. By this equation, the shape of the surface after machining is defined. The trajectory of the point on the cutter tip can also be very accurately described in the cutting zone by the circle of curvature.

Spremenjena enačba poti točke na konici noža v koordinatnem sistemu, ki je za kot poševnosti skobeljnega vretena zavrten okoli osi z, določa geometrijsko obliko odrezka in teoretično obliko površine pri odrezovanju v pravokotni ravnini na os skobeljnega vretena. Ker komponenta krivulje v smeri osi skobeljnega vretena ne vpliva na geometrijsko obliko odrezovanja, se enačba, ki opisuje obliko odrezka v tej ravnini, poenostavi v enačbo podaljšane cikloide. Prostorski problem se tako poenostavi v ravninski. Vpliv kota poševnosti skobeljnega vretena na kote odrezovanja je zelo majhen in ga lahko za običajne pogoje skobljanja zanemarimo. Kot poševnosti skobeljnega vretena vpliva na obliko odrezka in na teoretično obliko površine po obdelavi.

Vpliv neenakih polmerov odrezovalnih nožev skobeljnega vretena na kakovost obdelane površine je lahko zelo velik. Posebej je bil raziskan vpliv izsrednosti skobeljnega vretena na obliko obdelane površine. Pri izsrednem skobeljnem vretenu se zmanjša vpliv kota poševnosti skobeljnega vretena na največjo višino profila obdelane površine.

Karakteristike realne površine so določene z meritvijo profila te površine za dve vrsti lesa, in sicer bukov in smrekov les. Profil obdelane površine je naključna ustaljena funkcija. Za analizo topografskih značilnosti tako nastale površine so bile uporabljene statistične metode za analizo naključnih procesov.

Profili obdelane površine imajo močno izraženo periodičnost. Periodičnost je razvidna tako iz avtokorelacijske funkcije kakor tudi iz gostote energijskega spektra. Frekvenca oziroma valovna dolžina nosilnega vala profila se ujemata z izračunanimi karakteristikami teoretično izračunanega profila. V razmerah, v katerih je bila opravljena raziskava, določa valovno dolžino in amplitudo te periodičnosti z največjim vplivom pot rezalnih robov posameznih nožev skozi obdelovanec. Poleg te najvplivnejše frekvence določa obliko nastalega profila še naključni vpliv, ki je posledica anatomskih značilnosti strukture lesa.

Zelo značilna karakteristika profila površine je standardno odstopanje nagiba profila. Vrednosti za standardno odstopanje nagiba so za bukov les večje kakor za smrekov les. Anatomske značilnosti posamezne vrste lesa torej vplivajo na karakteristike profila površine, nastalega po obdelavi. Razlika med standardnim odstopanjem nagiba profila pri kotu poševnosti skobeljnega vretena 0° in 30° je pomembna pri podajalni hitrosti 22,56 m/min za obe vrsti lesa. Vrednosti za standardno deviacijo nagiba so za obe vrsti lesa večje pri kotu poševnosti skobeljnega vretena $\lambda = 30^\circ$.

The transformed equation for the trajectory of the point on the cutter tip in the coordinate system, which is turned by the planing spindle angle of inclination around z-axis, defines the geometry of the chip and the theoretical shape of the surface after cutting in a plane perpendicular to the axis of the planing spindle. Since the curve component in the direction of the planing spindle does not affect the geometry of cutting, the equation describing the form of the chip in this plane can be simplified into an equation for a lengthened cycloid. A problem in space is thus simplified into a planar problem. The effect of the planing spindle angle of inclination on the angles of cutting is very small and can be neglected in commonly used cutting conditions. The planing spindle angle of inclination has some influence on the form of chip and on the theoretical shape of the surface after machining.

The effect of unequal radii of planing spindle cutters on the generated surface quality can be considerable. Special attention was given to the effect of planing spindle eccentrity on the shape of the generated surface. An eccentric planing spindle reduces the effects of the planing spindle angle of inclination on the generated surface profile peaks.

The characteristics of the real surface are defined by measuring the profiles of two kinds of wood, i.e. beech and pinewood. The generated surface profile is random stationary function. In the analysis of the topographical characteristics of the surface, thus created reference was made to statistical methods for the analysis of random processes.

The generated surface profiles have a strongly expressed periodicity. The periodicity is evident both from the autocorrelation function and from the energy spectrum density. The frequency or the wave length of the dominant profile wave correlates with the calculated characteristics of the theoretically calculated profile. In the given conditions, the wave length and amplitude of this periodicity are defined mostly by the cutting edge path of a particular cutter through the workpiece. In addition to this most influential frequency, the shape of the generated profile is defined also by random effects having their reason in the anatomy characteristics of the wood structure.

A significant characteristic of the surface profile is the standard deviation of the profile inclination. The standard deviation values are higher for beech wood than for pine wood. Thus we can conclude that the anatomy features of a particular kind of wood have an effect on the characteristics of the surface profile generated after machining. The difference in the standard deviation of profile inclination at a planing spindle angle of inclination 0° to 30° is significant at a feed rate 22.56 m/min for both kinds of wood. The values of the standard deviation of inclination are higher for both kinds of wood at a planing spindle angle of inclination $\lambda = 30^\circ$.

Le pri obdelovancu iz bukovega lesa pri podajalni hitrosti 42,65 m/min je razvidna pomembna razlika za srednje odstopanje profila R_a. V ostalih treh primerjavah ni mogoče dokazati vpliva na srednje odstopanje profila R_a in s tem izboljšanja kakovosti površine pri skobljanju s poševno postavljenim skobeljnim vretenom. Razlog za to je povečan vpliv naključne komponente pri poševno postavljenem skobeljnem vretenu na obliko površine. Iz študija kinematike orodja pričakovana prednost poševnega skobljanja v tej točki torej ni potrjena.

Only in the workpiece from beech wood and at a feed rate 42.65 m/min we can note a significant difference in the mean deviation of the profile R_a. In the other three comparisons it is not possible to prove any effect on the mean deviation of the profile R_a and thus an improvement of surface quality in planing with an obliquely positioned spindle. The reason for this is a bigger influence on the shape of the profile, of the random component with an obliquely positioned spindle. Thus, from the study of tool kinematics, the advantage expected of oblique planing was not confirmed in this point.

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