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Concept of advanced technology development of special technological equipment for processing industry

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Abstract: The paper deals with the manufacturing technology of refiner plates that are used for preparing the paper pulp in the paper industry. The manufacturing technology consists of casting, heat treatment, machining and balancing. Special attention is given to the selection of materials used for casting of the refiner plate segments, and to defining the appropriate heat treatment in order to make the tools with optimal technical characteristics. Defining the technological parameters for the process of plain grinding of the refiner plate as well as noting the few negative effects occurring during the grinding process are presented in the paper. The paper also pays attention to the influence of machining technology on the micro-surface of the cutting elements, because it has a significant influence not only on the cutting edge but even on the surface quality and the total consumption of energy in the cutting process.

Koncept napredne tehnologije izrade specijalne tehnološke opreme za procesnu industriju

Izvornoznanstveni članak

Sažetak: U radu je opisana tehnologija izrade diskastih pločastih noževa koji se koriste za pripremu papirne mase - pulpe u industriji papira i celuloze. Tehnologija izrade sastoji se iz lijevanja, toplinske obrade, strojne obrade i uravnoteženja. Naročita pažnja u ovom radu posvećena je definiranju materijala koji se koristi za lijevanje pločastih noževa i projektiranju odgovarajuće termičke obrade kako bi dobili alate potrebnih tehničkih karakteristika. Definiranje tehnoloških parametara za proces ravnog brušenja pločastih noževa i neke negativne pojave u procesu brušenja također su dati u ovom radu. Rad ukazuje na utjecaj tehnologije obrade na mikropovršinu reznih elemenata, a koja ima bitan utjecaj kako na rezni rub tako na kvalitetu površine i ukupan utrošak električne energije u procesu mljevenja.

1. Introduction

The extent of fiber cutting during the preparation process of the paper pulp will decisively affect the mechanical and optical properties of the paper, as it will regulate the proportion of long and short fibers in paper. The aim of the cutting and grinding is to achieve a fiber composition that yields the best properties of the material used in the paper production process. The results of the cutting during the preparation of the pulp are determined not only by technological characteristics and cutting regime but also by the factors related to the technical and technological characteristics of the refiner plates (*Figure 1*). One of the most common problems encountered by researchers dealing with paper technology is the cutting geometry and manufacturing technology of the refiner plates. In the industrial production of paper, efforts are made to manufacture high quality paper with as low production costs as possible. The concept of technology used for manufacturing of the refiner plate is presented here. The concept provides good cutting characteristics and low consumption of electric energy during the cutting process.

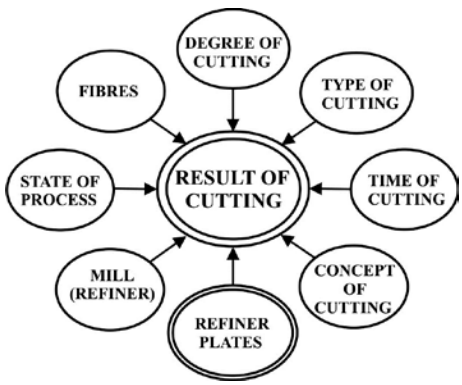


Figure 1: Factors influencing the results of paper mass cutting

Slika 1: Utjecajni faktori na rezultate mljevenja papirne mase

Symbols/Oznake

SEL	- Specific Edge Load - specifično rubno opterećenje	s	- side movement of the grinding table after one stroke, mm/w - bočno pomicanje stola brusilice nakon jednog hoda
P_m	- cutting power, W - snaga mljevenja	B_t	- the width of grindstone during peripheric grinding, mm - širina tocila pri obimnom brušenju
n	- number of revolutions of mill rotor, o/min - broj okretaja rotora mlina	B_c	- the width of grindstone face during face grinding, mm - širina čela tocila pri čeonom brušenju
z_r , z_s	- number of rotor and stator teeths, respectively - broj zubi rotora odnosno statora	T	- the steadiness of the grindstone, min - postojanost tocila
l	- length of tooth, m - dužina zubi	C_v,x,y,m,z	- machining parameters - parametri obradivosti
b	- tooth width, m - širina zuba		**Greek letters/Grčka slova**
R	- segment radius, m - polumjer segmenta	θ	- angular parameter of refiner plate segment - kutni parametar segmenta pločastog noža
g	- tooth inter-space, m - širina međuzublja	α	- mean angle of cutter edge - srednji kut obruba noža
L	- difference between the exterior and interior radius of the disc of the set, m - razlika vanjskog i unutarnjeg polumjera diska garniture	x	- number of sectors with the same form of cutting geometry - broj sektora sa istim izgledom rezne geometrije
L_s	- secondary length of cutting edges of the set of cutters - sekundarna duljina reznih ivica garniture noževa	β	- angle between the cutting edge and the rightmost edge of the sector - kut između reznog ruba i desnog krajnjeg ruba sektora
C_r, C_s	- the intersection of cutting edges of the rotor and stator cutters, respectively, m - mjera križanja reznih ivica rotorskog i statorskog noža	γ	- cutting angle - kut sečenja
MEL	- specific edge load - specifično rubno opterećenje		
v_r	- bench speed, m/min - brzina radnog stola		

2. The technical and technological characteristics of refiner plates

Milling cutters come in several shapes and sizes but usually as segments or plates. Therefore, technical and technological characteristics can be classified into four groups: plate geometry, geometry of cutting elements (teeth), material of the cutters, and the micro-geometry of cutting face. Basic components of the above mentioned groups are shown in *Figure 2*.

According to [1, 2], the refiner plate is characterized by: specific edge load, the angle of cutting tooth edge, the tooth geometry, and the geometry of the tooth inter-space.

2.1. Specific edge load

The technological and energy results of the cutting are influenced by the intensity and frequency of cutting tooth edges acting on the fibers. Also, high quality paper depends on the amount of energy per kilo of fiber. On the basis of these requirements, an index is defined that represents the intensity and frequency of the cutting tooth edges acting on fibers. In most presentations this index is the specific edge load, expressed by Equations (1) and (2), [3].

$$SEL = P_m / L_s \text{ [J/m]} \quad (1)$$

$$L_s = z_r \cdot z_s \cdot l \cdot n/60 \text{ [m/s]} \quad (2)$$

P_m [W] – cutting power,
n (o/min) – number of revolutions of mill rotor,
z_r , z_s – number of rotor and stator teeths, respectively,
l [m] – length of tooth
L_s – secondary length of cutting edges of the set of cutters

2.2. Angle of cutting tooth edge

The angle of the cutting tooth edge affects the cutting intensity. A tooth of the refiner plate segment having relatively larger angle of cutting edge intersects more teeth of the refiner plate against the opposite disc. In order to define and integrate the angle of cutting edge into a model, it is assumed that the geometry of the teeth and the teeth inter-space is constant with defined angles (*Figure 2*), [3].

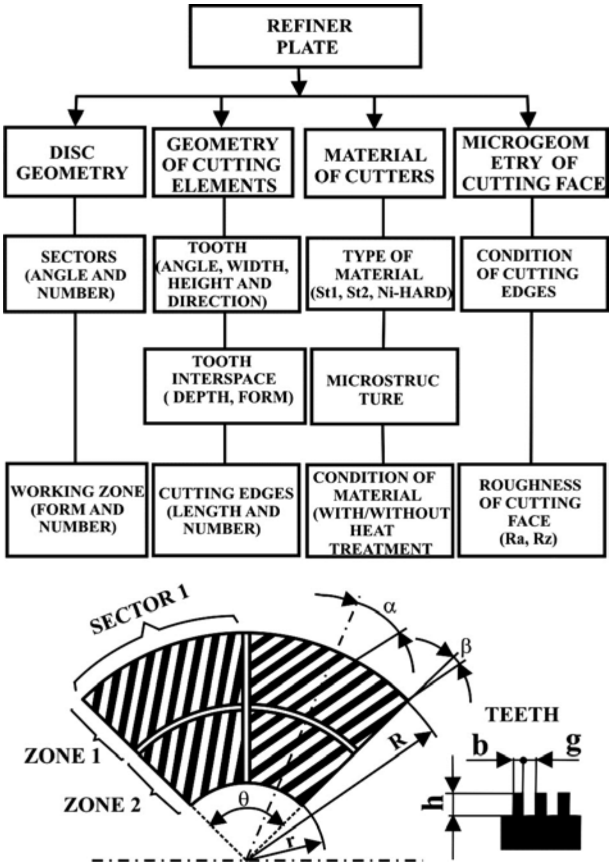


Figure 2. Technical and technological properties of refiner plate

Slika 2. Tehničke i tehnološke karakteristike diskasto-pločastih noževa

The cutting disc with teeth is composed of segments (refiner plates) that usually have the same angle (θ). The segment has more sectors (x) having the same form of cutting geometry. The mean angle of cutter edge (α) is defined by the segment radius (R) and by the line passing through the centre of the sector. In practice, the angle (β) is measured, i.e. the angle between the cutting edge and the rightmost edge of the sector. The mean angle is expressed by *Equation (3)* and it always has a positive value.

$$\alpha = \beta + \frac{\theta}{2 \cdot x} \tag{3}$$

In practice, the rotor and stator geometry will be identical, so the cutting angle is obtained by *Equation (4)*:

$$\gamma = 2\alpha \tag{4}$$

In practice, the lengths of the cutting edges of a refiner plate will differ (*Figure 2*). So according to [1, 4, 5] the system is modeled by the teeth arrangement. It is presented in *Figure 3*, i.e. the teeth are arranged on the cylinder, not on the plate. In that case, the value (*L*) corresponds to the difference between the exterior and interior radius of the disc of the set, so the lengths of cutting edges are equal.

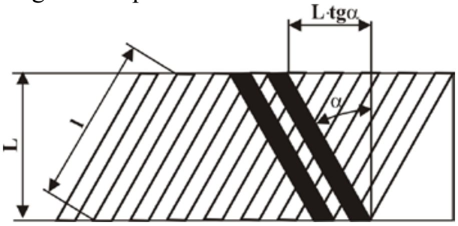


Figure 3. Modeled length of teeth of refiner plate

Slika 3. Modelirana dužina zubi diskasto-pločastih noževa

The intersection of cutting edges of the rotor and stator cutters is given by *Equations (5)* and *(6)*, respectively:

$$C_r = L \cdot \mathrm{tg}\alpha_r \tag{5}$$

$$C_s = L \cdot \mathrm{tg}\alpha_s \tag{6}$$

The secondary length of the tooth edge L_s is added to *Equations* (5) and (6), and it is marked as $L_{s\gamma}$. Since $l = L / cos\alpha$ already is included in *Equation (2)*, then $L_{s\gamma}$ can be expressed by Equation (7) for entire set of cutters:

$$L_{s\gamma} = L_{ss} tg\alpha_s + L_{sr} tg\alpha_r \ \text{[m/s]} \tag{7}$$

If the refiner plates of stator and rotor are identical, *Equation (7)* will be transformed into Equation (8):

$$L_{s\gamma} = 2L_s tg\alpha \tag{8}$$

The expression for specific edge load is also transformed as:

$$SEL_\gamma = \frac{P_m}{L_{s\gamma}} \ \text{[J/m]} \tag{9}$$

2.3. Geometry of the teeth

According to the cutting theory, [3] it is known that the tooth edges make fiber shorter and that tooth faces separate fibers longitudinally. Tooth interspaces allow the transport of fiber suspension through the set, and they are of great importance when fiber treatment is in question. Narrowing of the groove will increase the risk of fibers staying along the tooth edge for longer periods of time. The cutting process is influenced by tooth width (*b*) and by the width of the tooth inter-space (*g*), *Figure 1*. These two widths influence the cutting process in the following manner:

$$k = \frac{b}{b+g} \tag{10}$$

Specific edge load, with the influences of cutting angle, tooth width and width of tooth inter-space, is called the modified edge load, and is expressed by *Equation (11)*:

$$MEL = \frac{P_m}{L_{ss} \cdot tg\alpha_s \frac{b_s}{b_s + g_s} + L_{sr} \cdot tg\alpha_r \frac{b_r}{b_r + g_r}} \tag{11}$$

In the general case of identical geometry of rotor and stator, the modified edge load is given by *Equation (12)*:

$$MEL = \frac{P_m}{2L_s tg\alpha \frac{b}{b+g}} \tag{12}$$

Finally, tooth height (*h*) is defined by the strength of the tooth base, and it is based on *MEL* and mechanical characteristics of the material that refiner plate is made of. Tooth height also depends on the width of tooth inter-space. Recommended width depends on the the requirements of the pulp flow speed through tooth inter-space (*Figure 2*).

The stated theoretical analysis is used under production conditions of defining the cutting geometry, while detailed analysis, including the angular rotation of rotor disc, is given in references [1, 3]. The cutting geometry of refiner plate is usually defined by engineers engaged in paper technology.

3. Manufacturing technology of refiner plate segments

Standard manufacturing technology of refiner plate segments consists of casting the melted metal of specific composition in special moulds made of sand and bentonite. The mould matrixes have the shape of a refiner plate segments and they are filled with liquid metal. The refiner plate segments are often made by milling on CNC machines with previously prepared plates having specific chemical composition. Before balancing, both methods undergo different processes of mechanical and heat treatment.

According to the methodology presented in this paper, the manufacturing technology of refiner plate consists of casting, heat treatment, machining, and static and dynamic balancing. The total manufacturing flow diagram is shown in *Figure 4*.

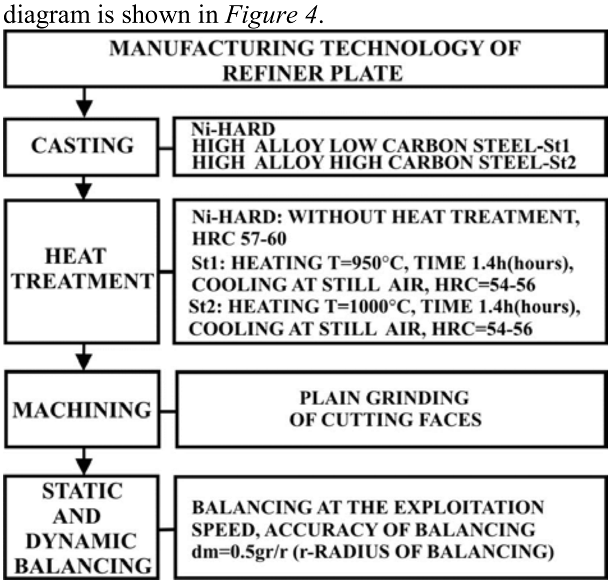


Figure 4. Total manufacturing technology of refiner plate

Slika 4. Globalna tehnologija izrade diskasto-pločastih noževa

Casting of the refiner plate segments is done in the moulds made in the "HOT-BOX" procedure [6], i.e. the moulding sand (quartz sand of fine granulation with 4% of resin) is blown into the metal moulds at the temperature of 300-400 ^{0}C.

The above mentioned sand is blown into the warm tool having the shape of refiner plate segments and it is subjected to the appropriate heat regime. *Figure 5* shows 'HOT-BOX' moulding method.

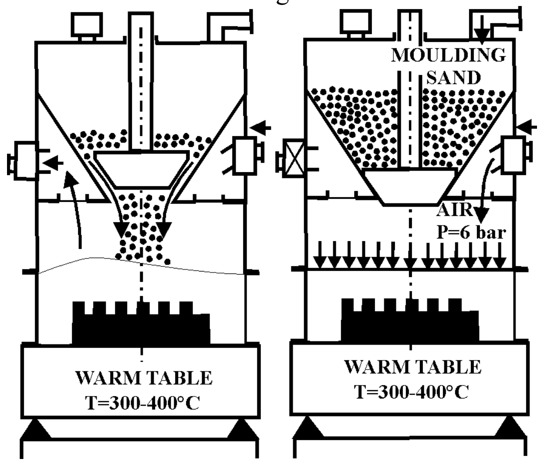


Figure 5. 'HOT-BOX' moulding method

Slika 5. "HOT-BOX" metoda izrade kalupa

For clear understanding of technological process of casting, the tools used for mould shaping and the sandy mould are shown in *Figure 6a* and *Figure 6b*, respectively. The casting is shown in *Figure 6d*.

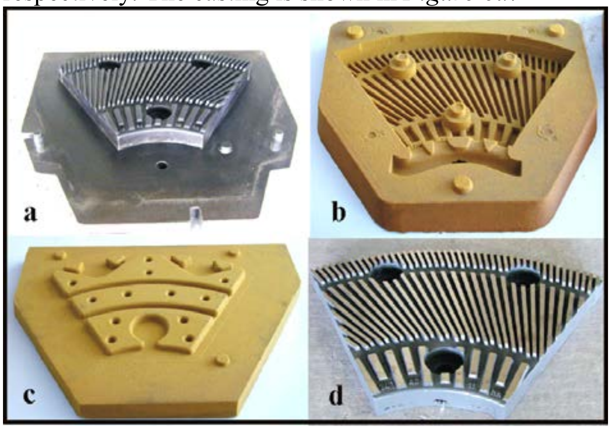


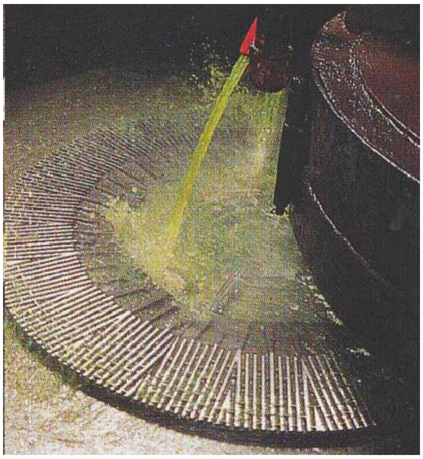
Figure 6. Tool (a) and moulds (b, c) used for casting the segments (d) of refiner plate

Slika 6. Alat (a) i kalupi (b, c) korišteni za lijevanje segmenata (d) diskasto-pločastih noževa

After casting and heat treatment, machining of the castings is done according to the following technological regime. First, castings are prepared for the process by plain grinding. Plain grinding includes rough and fine grinding. Plain grinding can be done by peripheral grinding during rectilinear motion of the bench, or by face grinding during rectilinear or circular motion of the bench. The methods of grinding the refiner plate segments are shown in *Figure 7*.

a)

b)



c)

Figure 7. Methods of plain grinding: a) peripheric, b) rectilinear, and c) circular grinding

Slika 7. Metoda ravnog brušenja diskasto-pločastih noževa: a) obimno, b) pravolinijsko i c) kružno brušenje

The grinding regime which is applied to the plain surfaces containing teeths and tooth interspaces [7, 8] is expressed by the following equations:

Plain peripherical grinding:

$$v_r = \frac{C_v B_t^y}{T^m t^x s^y} \quad (13)$$

$$s = \frac{C_v}{T^{0.5} v_r t} \quad \text{(rough grinding)} \quad (14)$$

$$s = \frac{C_v}{v_r t} \quad \text{(fine grinding)} \quad (15)$$

Face grinding by rectilinear and circular motion of the bench:

$$v_r = \frac{C_v}{T^m t^x B_c^z} \quad (16)$$

where:

v_r [m/min] – bench speed,

s [mm/w] – side movement of the grinding table after one stroke,

B_t [mm] – the width of grindstone during peripheric grinding,

B_c [mm] – the width of grindstone face during face grinding,

T [min] – the firmness of the grindstone,

C_v, x, y, m, z – machining parameters depending on the grinding method, material of refiner plate, grindstone material etc.

Cutting speed, i.e. the speed of the peripheral grindstone v_t [m/s], as well as the quality of the grindstone, depends on the material of the refiner plate, cooling medium, grinding method, grindstone material, etc. [7, 8, 9].

The refiner plates (which are plain ground and laterally set at the defined sector angle) are statically balanced at defined points, and after having been dynamically balanced at the working speed on a special balancing machine with the accuracy of 0.1% by the method of mass adding (*Figure 8*).

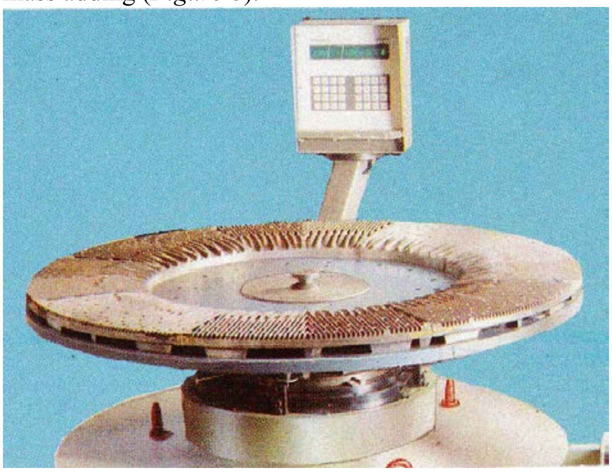


Figure 8. Balancing machine

Slika 8. Stroj za balansiranje diskasto-pločastih noževa

The complete manufacturing technology along with the accompanying technical and technological documentation is shown in *Figure 9*.

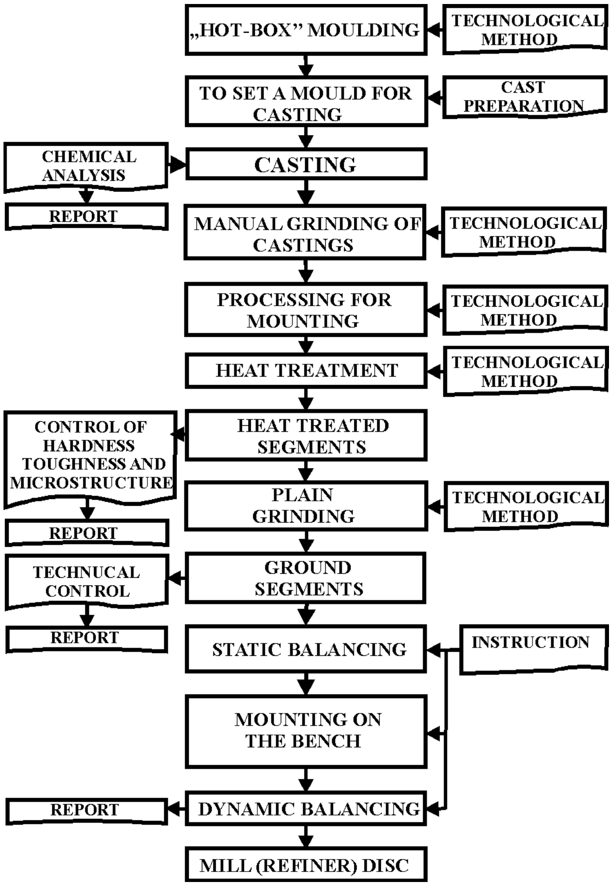


Figure 9. Complete manufacturing technology of refiner plate

Slika 9. Ukupan koncept tehnologije izrade diskasto-pločastih noževa

4. Defects which may occur during manufacturing process

4.1. Brittleness of the cutting teeth

Chrome and nickel are important alloying elements of the material used for casting the refiner plate segments. Chrome improves the resistance to wear, and nickel improves the toughness which is a significant characteristic for the conditions of paper mass cutting [11]. Steel containing a high percentage of chrome is highly wear-resistant after heat treatment. But, if the heat treatment is not done by any appropriate method, cutting teeth may become much more brittle or their resistance to corrosion may be reduced. Over brittleness of the cutting teeth is unfortunate because of the dynamic conditions of cutting. Resistance to corrosion is very important for refiner plates which operate under aggressive conditions. Thus, besides chemical composition of casting material and cutting hardness, the microstructure, which may be influenced by appropriate heat treatment, is also important for the manufacturing technology of refiner plates (*Figure 4*). The microstructure of cutting teeth cast of Ni-Hard is shown in *Figure 10.*

Figure 10. Microstructure of cutting teeth cast of Ni-Hard

Slika 10. Mikrostruktura rezne površine diskasto-pločastih noževa lijevanih od Ni-Harda

4.2. Micro-cracks of the cutting face

According to [10], when the cutters are subjected to plain grinding, special attention should be paid to defined cutting regimes (the quality of the grindstone, longitudinal and transverse pitch of the bench, quantity and type of cooling fluid), because an inappropriate cutting regime may influence not only mechanical but micro-structural properties of the tooth faces, the sharpness of cutting edges, and micro-cracks which cause more intensive initial wear, and the scraping of tooth edges. Scraping of tooth edges is undesirable, as it causes improper cutting, it may overload the mill, make noise and vibrations, which influences the system's reliability. During the sharpening of cutting teeth, some elements of the grindstone are improperly parted, which leads to improper sharpening of the tooth edge (the cutting edge is deformed). This defect may usually be eliminated by rough and fine grinding. Rough grinding is done by the regime which does not result in thermal stress of the cutting face. Fine grinding is done in a dozen stages with very small cutting depths, [7]. The influence of the cutting regime on the hardness of cutting tooth face is presented in *Figure 11.*

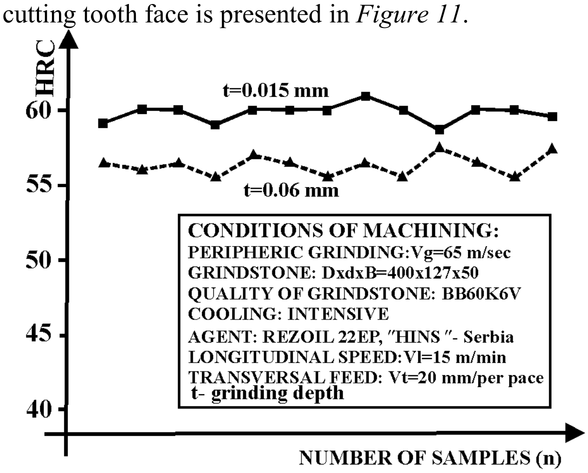


Figure 11. The influence of cutting regime on the cutting face

Slika 11. Utjecaj režima obrade na tvrdoću rezne porvršine zuba

5. Results of cutting done by the experimental set of refiner plates

During a trial exploitation we observed the energy results of cutting done on a set of "Sprout-Bauer" discs whose diameter is 24in. The cutters on one of the operating discs had the following chemical composition: C=3.54%, Si=0.71%, Mn=0.42%, Cr=2.89%, Cu=0.048%, Mo=0.173%, Ni=3.85%, V=0.022% and those cutters were cast of black sand and bentonite. These cutters were made according to the conventional technology (KT cutters). On the other disc of the same diameter there were the cutters having the following chemical composition: C=3.38%, Si=0.79%, Mn=0.915%, Cr=2.51%, Mo=0.178%, Ni=4.03%, V=0.020%, W=0.123%. These cutters were made according to a new concept (NT cutters).

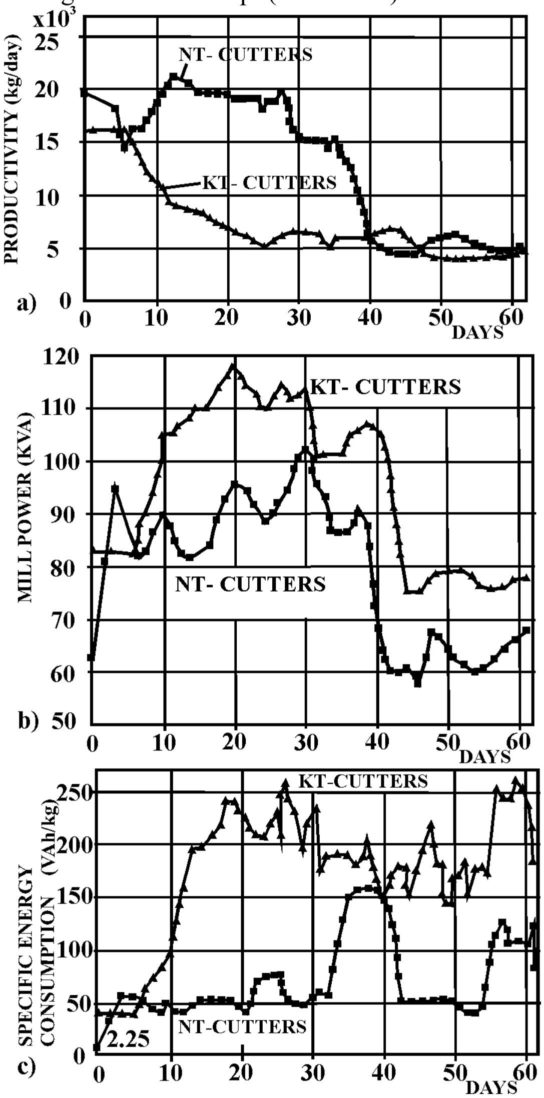


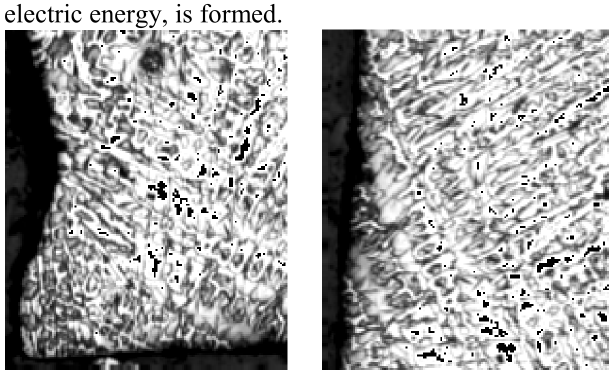
Figure 12. A comparison of cutting done by the refiner plates manufactured according to the conventional and the new concept of technology

Slika 12. Usporedba mljevenja diskasto-pločastih noževa proizvedenih u skladu sa konvencionalnim i novim konceptom tehnologije

The moulds made according to the new concept were painted with zircon coat, and since they were made of moulding sand their surfaces were smooth and flat, which lowered the resistance to mass flow through the tooth interspace. Zirconium is added in order to make additional micro-alloying of the tooth face which is important for forming the cutting edge after the grinding.

Figures 12a, *12b*, and *12c* show comparative results from the measurement with respect to productivity, disc power, and specific energy consumption for the cutting process done by means of KT and NT cutters. During initial wear (i.e. during the first five days) the cutting process done by KT cutters is better, but after that period of time the cutters made by the new concept of technology had advantages.

Cutting done by means of NT cutters during initial wear of the cutting face is worse because of undersharpness of the cutting teeth of the plate-like cutters, *Figure 13a*. If the cutting faces are subjected to both rough and fine grinding the stated problem is avoided. The profile of properly sharpened tooth, i.e. the teeth of refiner plates made by the new manufacturing concept, is shown in *Figure 13b*. It should be mentioned that the tooth faces of the set of working discs are equally worn, because during the cutting process the cutting edge, which provides proper fiber cutting and lower consumption of electric energy, is formed.



a) *b)*

Figure 13. Profile of a cutting tooth of the refiner plate: a) improperly sharpened, b) properly sharpened

Slika 13. Izgled reznog profila zuba pločastih noževa a) loše naoštren, b) ispravno naoštren

6. Conclusions

In order to develop the manufacturing technology of the refiner plates, the scientists direct special attention to studying the influence of the grinding process (grinding thermodynamics) on the micro-structural changes of the cutting faces which may significantly affect the cutting edge (intensive wear), tool life, total consumption of cutting energy, dynamic stability of machine, and system efficiency.

The set of refiner plates, made by the new concept, has the same geometric characteristics as the set of refiner plates made by a well-known European manufacturer (the cutters made by standard technology: mean angle of cutting edge is α = 27°, the coefficient of tooth width and interspace width is k=0,52). By the above mentioned set we have achieved better results in view of the quality of fiber treatment, especially in view of the specific energy consumption of the discs. The better results are caused by:

- The concept of the new manufacturing technology: cutting characteristics depends not only on the chemical composition of casting but even on the manufacturing technology of the moulds whose surfaces are painted with zirconium.
- After the appropriate regime of heat treatment, the grinding process includes two phases (rough and fine grinding), in order to avoid in order to avoid fraying while achieving sharp edge of the cutting tooth.

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