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Impact of various factors on the cutting performance of knives when processing food products

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Abstract. Determining the optimal geometric and kinematic characteristics of the working components is crucial for ensuring the quality performance of machines used in the cutting of semi-finished macaroni products. These characteristics define the primary operational properties of the working components, such as cutting ability, stability, and durability, and their appropriate selection ensures the technological reliability of cutting machines. The research presented in this article aims to investigate the dependence of a knife's cutting ability on a set of factors, including the type and conditions of the cutting process, the geometry of the knives, and the cutting force. The study involves an analytical examination of the cutting ability of knives during three main periods: running-in, steady-state, and blunting. Additionally, a block diagram is developed to optimize the parameters of the knife's microgeometry. The research methods employed include analytical investigations using engineering calculations.

1 Introduction

Cutting is one of the technological methods of mechanical processing of various materials. Due to the difference in the physical-mechanical qualities of the material, which determine the factors affecting the cutting process, various requirements are imposed on the modes and methods of cutting and cutting tools. Cutting food products into half-finished goods is a kind of destruction of materials. It is distinguished by the peculiarities of the execution of dividing a part with a cutting tool into components with predetermined dimensions and the quality of the separated surface.

Knife cutting ability is commonly defined as the ability of the blade's working surface to create a stress state in the zone of contact with the material being separated, resulting in the material's destruction. Cutting ability is the most important indicator of knives used in the processing industry and largely determines the efficiency of cutting machines in terms of quality and energy indicators. Cutting ability depends on a complex of factors, including the type and conditions of the cutting process, knife geometry, cutting speed, etc.

Sliding cutting offers a "smooth" method for processing plant materials in bioconversion processes, where the primary energy is utilized for releasing fibrils and creating new surfaces. This approach can lead to a threefold increase in the yield of the final product (glucose) with

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minimal energy consumption [1]. In industries such as canning and vegetable drying [2], employing the sliding cutting technique ensures consistent processing of raw materials, resulting in a flat and smooth cut surface. This method helps reduce cell damage and vitamin C loss. Consequently, in the sugar industry, implementing sliding cutting enhances juice circulation in diffusion installations, leading to improved final product yield [3].

The pioneering work of T.I. Egorova in the study of cutting and cutting edges focused on investigating the impact of blade roughness and size on cutting force, particularly in cutting straw stalks [4]. T.I. Egorova observed that the cutting force during chopping is independent of roughness, with an increase in friction forces occurring.

Researchers studying the influence of microgeometry on the cutting process have considered various parameters as characteristics of the cutting edge's microrelief. For instance, A.A. Ivashko includes factors such as the blade thickness and tortuosity, the height of microcutting element protrusions, the angle of edge inclination to the blade line, the width of the cavity between microelements, and the step between blade peaks [5].

Some studies define cutting ability as the blade's capacity to concentrate the applied force at the edge. This ability increases with greater blade sharpness and decreases with a smaller sharpening angle. The lower the force required to create destructive stresses under the edge, the higher the cutting ability. Accordingly, N. E. Reznik interpreted cutting power as the reciprocal of the total cutting force [6].

The cutting ability of a blade is characterized by the ratio of the pitch of microroughnesses (S) along the cutting edge to the height of microroughnesses (Ra). It was found that during the initial period of knife operation, the S/Ra ratio was 2.5-3.0, while at the end of the persistence period, this ratio was 10-11 [7].

O. P. Renzyaev investigated [8] the influence of cutting tool microgeometry characteristics on the sliding of bakery and flour confectionery products. He defined the cutting ability of a knife as a function of its microgeometric and geometric parameters, depending on the kinematics of cutting, sliding, and the properties of the semi-finished product. The author obtained regression equations that establish the relationship between the characteristics of the grinding wheel, sharpening modes, and the hardness of the knife material with the cutting-edge microgeometry characteristics.

O. P. Renzyaev found that the limited value of the width of the cutting edge should be considered the value of 40 microns because its excess leads to a drop in the quality characteristics of the cut and an increase - because of returnable waste. At this point, the micro-teeth of the blade are completely smoothed out.

At present, it can be stated that, in addition to traditional work in the field of analysis of the mechanics of cutting food materials (power characteristics, modes, geometry of knives), research aimed at studying the main operational properties of working members (their durability, cutting ability, rigidity and stability, which have a direct impact on the energy and quality indicators of equipment operation) is becoming more and more developed.

2 Materials and methods

The research aims to determine the dependence characteristics of the cutting ability of a knife on a complex of factors, including the type and conditions of the cutting process, the geometry of the knives, and the cutting force in various periods of work. For this, the following tasks are solved: analytical study of the cutting ability of knives during three main periods of work: running-in, steady-state period, and blunting; development of a block diagram for optimizing the parameters of the microgeometry of knives. The research method is an analytical study of determining the cutting ability of knives at the stages of normal operation and during the period of dulling can be obtained.

During sliding cutting, the leading role is played by the microgeometry of the cutting part of the knife, i.e., the blade. Let us imagine the cutting edge (Figure 1) as a set of conical protrusions with a rounded vertex (radius of the rounding of the vertex r_l, angle at the vertex 2g, and transverse step of the protrusions S_n) [9].

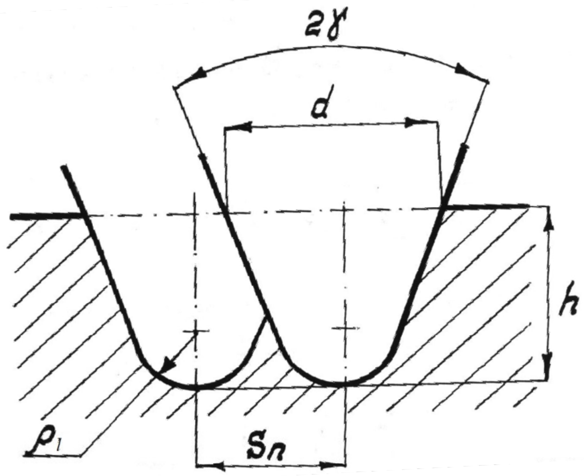

Fig. 1. Model of the cutting edge in cross section.

Grinder diameter d_n (1) in the section located at the working height h of the microtooth:

$$d_n = 2\sqrt{\rho_l h - h^2} ath \leq (\rho_l - \rho_l \sin\gamma)$$

$$d_n = 2tg\gamma(h + \frac{\rho_l}{\sin\gamma} - \rho_l) ath > (\rho_l - \rho_l \sin\gamma) \quad (1)$$

The working H of a microtooth is determined by the kinematics of the sliding cut. Thus, a contact is formed in the form of a convex conical curved surface and is determined in [10] as the pitch distance S_m along the midline, the vertex angle γ and the sliding coefficient K_s:

$$h = \frac{S_m}{K_s + tg\gamma}. \quad (2)$$

Since the rigidity of the knife material is much greater than the rigidity of raw macaroni products, the cutting edge can be considered an absolutely rigid body. In the process of sliding cutting, micro-teeth are introduced into the material being cut.

To simplify the analysis, the authors replaced the force effect of the microtooth on the material with a planar one. The authors identified an element in the material that is in contact with the surface of the microtooth at poin X (Figure 2). The microtooth influences this element in the regular and tangential directions. The value of the normal force N_1 depends on the cutting direction.

The friction force F_1 is determined by the magnitude of the normal force and the coefficient of friction

Friction force F_1 corresponds to the value of normal F and $k_{friction}$

$$F_1 = fN_1 \quad (3)$$

F_1 and N_1 form the S_1. This F reflects the action of the microtooth on the material element at point X. It forms ∠ j c r - N_1, tg j=f. In this case, r S_1 forms ∠ - y with the slip vector of the blade. It is an ∠ of action [11] and, in the case when f is not defined by N_1, is called ∠ -th between the vector of the working area of the microtooth and the object of influence and the slip vector.

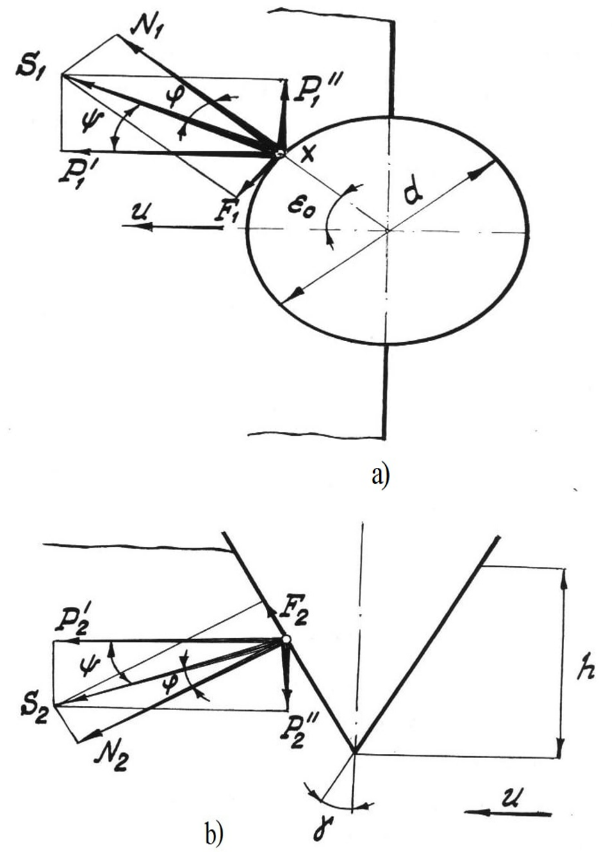

Fig. 2. Model of interaction between the forces of a microtooth and a part: a) horizontally; b) vertically.

The balance of forces at point X shows that:

$$F_1 = P_1^{'} \cdot \sin \varepsilon_0 - P_1^{''} \cos \varepsilon_0 \, ,$$
$$N_1 = P_1^{'} \cdot \cos \varepsilon_0 + P_1^{''} \sin \varepsilon_0, \qquad (4)$$

where:

N_1, F_1 are, respectively, the normal and tangential reactive forces of the action of the material on the microtooth at point X;

$P_1^{'}$is the force of the impact of the microtooth on the material at point X in the direction of cutting;

$P_1^{''}$is the force of lateral compression of the material at point X, acting normally to the direction of sliding;

$\varepsilon_0$is the current angle for the upper contour of the microtooth.

After setting (3) in (4) and transformations, we obtain a formula for determining the angle of action:

$$tg\psi = \frac{tg\varepsilon_0 - f}{1 + f \cdot tg\varepsilon_0} \qquad (5)$$

If $tg\varepsilon_0 = f$, ∠ = 0, then F - $P_1^{''}$= 0. If $tg\varepsilon_0 < f$, then ∠ - ψ changes changes sign to negative. This shows that F acts as a brake at X, where the element compacts, changes position with the microtooth, and is consistent with the sliding vector of the counterbody. I. V. Kragelsky [12] named the transition of interaction in the elastoplastic form during microcutting the boundary condition.

The authors classified the area of the object of influence during self-braking as a microcutting zone. This zone is located in the middle of a microtooth between 2 extreme points located symmetrically, where ∠ -. B of the microcutting zone equals l of the chord that corresponds to the central angle $2\varepsilon_0$, i.e.

$$l = d_n \sin \varepsilon_0 = d_n \sin arctgf \quad (6)$$

If we take *f=0,3*, then we obtain $l = 0{,}62h$. Above this value, the material will be elastic-plastic pushed in both directions beyond the limits of the microtooth contour.

When a microtooth moves, a hypothetical rod of a material with a cross-section will compress to an over-spec tensile strength. Destruction is fixed by slip lines, perpendicular to the direction of compressive loads [13].

Fig. 2b shows the F_n system in the vertical direction directed at the target. The authors replaced the curvilinear microtoothed surface with a flat one in the microcutting zone. The working surface carries out the action of forces $P_2^{'}$and$P_2^{''}$on the object of influence during the movement of the microtooth in the direction U. This produces a reaction forceN_2 and a friction force F_2.

The balance of power determines the following:

$$F_2 = P_2^{'} \sin \gamma - P_2^{''} \cos \gamma ,$$
$$N_2 = P_2^{'} \cos \gamma - P_2^{''} \sin \gamma \quad (7)$$

From these equations, if we put $F_2 = f N_2$and $tg\psi = P_2^{''}/P_2^{'}$, we obtain

$$tg\psi = \frac{tg\gamma - f}{1 + f tg\gamma} \quad (8)$$

In the same way as before, we note that the angle of action changes sign. In this case, the self-braking of the material in the contact zone begins and it begins to move with a microtooth. Since we took the positive value of the angle of action y based on the condition that the deformable material moves relative to the microtooth, characteristics of ∠ g, at which the angle y changes sign to negative, will determine the boundary condition for the transition from elastic-plastic deformations to cutting.

If we take f=1, then we get the limiting angle g=45°. At g=45°, the material will be destroyed by a microtooth (microcutting according to the qualification of I.V. Kragelsky [12]. Otherwise, the material is lifted by a microtooth, i.e., it experiences elastic-plastic displacement. If the average probable value of the angle gof the microtooth is more than 45°, then their conical part will not be able to perform microcutting.

In this case, a new surface will be formed with repeated deformation of friction areas, which increases the volume of wear products and falls in the quality indicators of sliding cutting. At any working height h and vertex radius r, the spherical vertex of the microtooth acts on the material in the same way.

The formation of a new surface occurs through repeated deformation of the friction track, resulting in an increase in the volume of wear products and a deterioration in cutting quality characteristics. The spherical tip of the microtooth exerts a uniform effect on the object at a working hardness level (H) for any characteristics and tip radius (r).

3 Results

The analysis of sliding cutting with one microtooth demonstrates the dependence of *b* of the microcutting zone in the horizontal plane on $k_{friction}$ and the working H of the tooth, which determines the size of the diameter of the grinder of its section.

At the same time, the smaller the working H of the tooth, the smaller the Ø of the contact of the microtooth, the less deformation of the material and the thinner the cut. In the vertical plane, the microcutting zone exists only with sufficiently sharp micro-teeth and high coefficients of friction between the material and the contact areas of the blade. Otherwise, the destruction of the material under the blade will occur under the successive action of the system of micro-teeth of the cutting edge in the mode of elastic-plastic deformation.

These circumstances allow determining the cutting ability of sliding cutting knives as a relationship between the penetration size H of the knife and the cutting side L:

$$Q = \frac{H}{L} \tag{9}$$

Developing the above relations for microcutting with a single tooth, in accordance with the theory of abrasive wear, we can write:

$$Q = q\frac{F_{act}}{F_a} \tag{10}$$

where Fa is contour contact area:

$$F_a = a \cdot l_b \tag{11}$$

a is b blade; lb is basic length;
q is specific parameter, which is equal to the relation

$$q = \frac{V}{F_{act} \cdot d} \tag{12}$$

d is the diameter of the microtooth section;
V is the volume of material interacting with the blade microteeth.

The works carried out earlier [5] showed that the value of V can be determined by the equation:

$$V = F_a\frac{h в \varepsilon^{\nu+1}}{\nu+1} \tag{13}$$

where:

Fact is actual contact area;
h is the working height of the microteeth;
в, ν is the characteristics of the curved support surface;
ε is the relative approach;
Rmax is the maximum H of microteeth.

Substituting (13) into (12) and (12) into (10), the authors obtained the following relation:

$$Q = \frac{h в \varepsilon^{\nu+1}}{d(\nu+1)} \cdot \frac{F_{act}}{F_a} \tag{14}$$

The actual contact area is practically equal to the diametrical section of the microtooth working surface and will be determined by the duration of the knife operation T. Experimental studies of the microgeometry of knives showed that sharpened knives (T=0) have a transverse pitch of microteeth $S_n \leq 2\rho_l \cos\gamma$. During normal operation, $S_n > 2\rho_l \cos\gamma$. Worn blades have $S_n \geq d$. Therefore, considering the known calculated ratios, the actual contact area of a single microtooth $Fact$ for the marked periods of work will be equal to:

1. Run-in stage:

$$F_{act}^1 = S_n \cdot h - \frac{S_n \rho_l}{2}(1 - cosarcsin\frac{S_n}{2\rho_l}) + \rho_l^2(\frac{\pi}{180}arcsin\frac{S_n}{2\rho_l} - \frac{S_n}{2\rho_l}). \tag{15}$$

2. Normal operation stage:

$$F_{act}^1 = S_n \cdot h - \frac{1}{2tg\gamma}(\frac{S_n^2}{4} - \rho_l \cos\gamma + \rho_l^2 \cos^2\gamma) - \rho_l(S_n - \rho_l \cos\gamma) \cdot \cdot (1 - \sin\gamma) + \rho_l^2\left[\frac{\pi(90-\gamma)}{180} - \cos\gamma\right] \tag{16}$$

3. Dulling stage:

$$F_{act}^1 = (\frac{\rho_l \cos\gamma}{tg\gamma} + h - \rho_l + \rho_l \cos^2\gamma)^2 tg\gamma - \frac{\rho_l^2 \cos\gamma}{tg\gamma} + + \frac{\pi\rho_l^2(180-2\gamma)}{360} - \frac{\rho_l^2 \sin\gamma}{2} \tag{17}$$

Since 2_m micro-teeth are involved in cutting, *S* of contact is equal to:

$$F_{act} = \frac{2l_b}{S_m} \cdot F_{act}^1 \tag{18}$$

Using the expression (14), (15), (18), it is possible to determine the cutting ability of knives, for example, for the run-in stage at large values of K_C:

$$Q = \frac{\left(\frac{Sm}{K_S + tg\gamma}\right) в \cdot \varepsilon^{\nu+1} \left[S_n \frac{Sm}{K_S + tg\gamma} - \frac{S_n \cdot \rho_l}{2}(1 - cosarcsin\frac{S_n}{2\rho_l}) + \right.}{(\nu + 1) \cdot a}$$

$$\frac{\left.\rho_l^2 (\frac{\pi}{180} arcsin\frac{S_n}{2\rho_l} - \frac{S_n}{2\rho_l})\right]}{Sm\sqrt{\frac{Sm}{K_S+tg\gamma}(2\rho_l - \frac{Sm}{K_S+tg\gamma})}}; \tag{19}$$

Similarly, formulas to determine the cutting ability of knives at the stages of normal operation and during the period of dulling can be obtained. Calculations show that the change in cutting ability is most noticeable during the transition from the run-in stage to normal operation.

The advantage of the obtained ratios for calculating the cutting ability of knives is that they consider the diverse characteristics of the blade microgeometry; the reflection of the three main periods of operation of the cutting tool – run-in, steady-state period, and dulling; and the possibility of experimental determination when cutting the mode R2 = const.

Analytical expressions obtained allow optimizing the parameters of the microgeometry of the blades according to the condition Q→max. For this purpose, an optimization program based on the use of the coordinate descent (ascent) method in the “Turbo Basic” language was developed. The flowchart of optimization is shown in Figure 3, and contains the following blocks:

Block 1. Input of initial optimization data. The designations in the flowchart and program are as follows:

h is the search step, eps is the relative depth of the teeth, e is the accuracy of the result, L is the current search step, gam is the contour angle, B, Nu are the coefficients, a(1) – is the work surface sharpening radius, a(2) is the longitudinal step of the microteeth, a(3) is the sliding coefficient, a(4) is the transverse step of microteeth.

Block 2. Assigning the current value of the search step to the variable L.

Block 3. Beginning of the optimization cycle by the method of coordinate descent (ascent).

Block 4. Adding the search step h to the optimization parameter.

Block 5. Referring to the subprogram for calculating the value of the cutting ability function and checking the constraints for the parameters.

Block 6. Storing the maximum value of the function f into the variable “C”.

Block 7. Storing the current value of the function f into the variable “max”.

Block 8. Checking the condition: is the current value of f greater than the last maximum value “C”. If the condition is met, then go to block 4. Otherwise, go to block 9.

Block 9. Reducing the length of the search step by 3 times and reversing it for searching in the “reverse” direction.

Block 10. Checking the condition for the size of the search step. When it is executed, go to block 4, otherwise - to block 11.

Block 11. The value of the search step h becomes equal to L.

Block 12. Transition to optimization for the next parameter.

Block 13. If not all parameters were used for optimization, then go to block 4.

Block 14, 15. Reducing the current search step by 9 times.

Block 16. Checking the condition for the accuracy of the performance characteristics search. If accuracy is not achieved, then go to block 3. Otherwise, go to block 17.

Block 17. Printing out the optimization results: the maximum value of the cutting ability function and the optimal values of all optimization parameters.

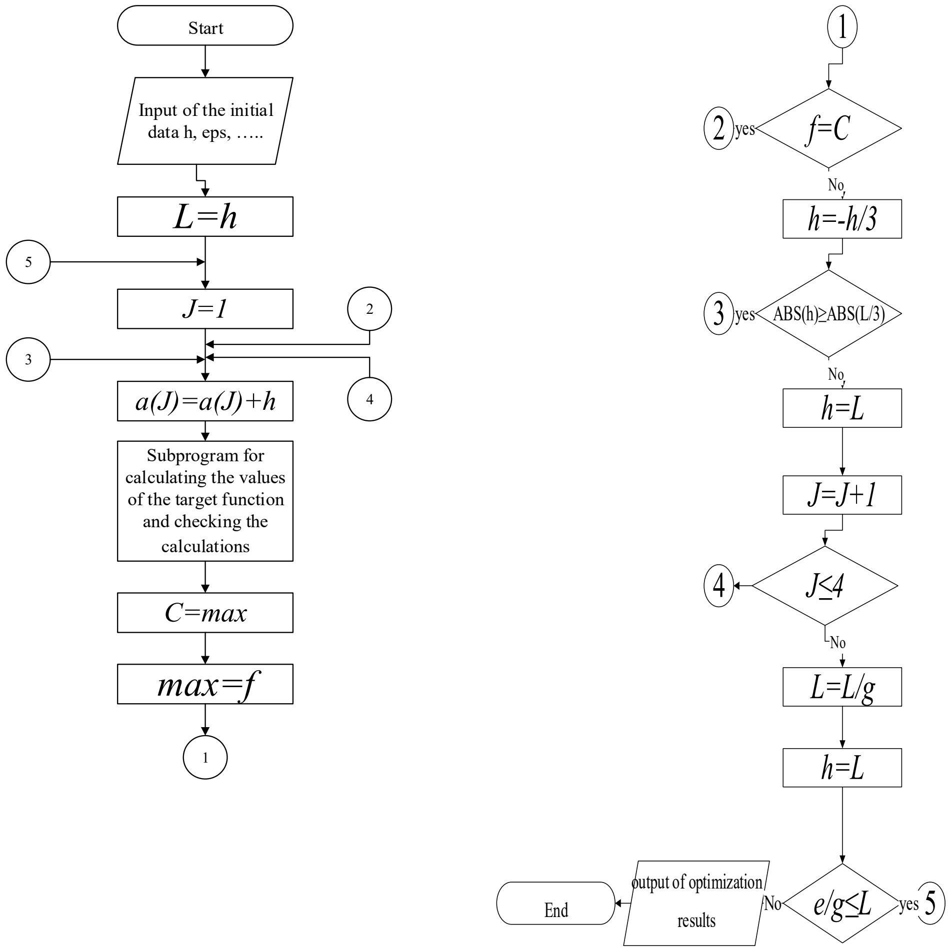

Fig. 3. Flowchart of optimization of micro-geometry parameters of the knives.

The implementation of the program showed that for the period of normal operation of the knives with a relative penetration of the microteeth $\varepsilon=0.3$, the optimal parameters are: slip coefficient K_C=14.4; the value of the coefficients of the curve of the supporting surface $в=1$, $\nu=1$, the contour angle $\gamma=45^0$, the radius of the blade sharpening ρ_l=16.3 micron; the pitch of the teeth of the longitudinal and transverse microprofiles, respectively, are equal to Sm=500 micron; Sn=32 micron

4 Discussion

According to [14], the data which are consistent with the data obtained by the authors, it was found that the shaping of the blade is conducted when the reliefs of the chamfers are crossed. Microgeometry is determined by the technical parameters of the sharpening process, material properties, F_n, arising during sharpening, and their vectors. Checking the value of the influencing factors determining the shaping of the working blades is carried out by dispersion analysis. Knife tests show that the material does not affect microgeometry. Usually, the ∠ of sharpening, vector, and grain size are investigated. The analysis of regression equations proves (which is also confirmed by the authors) that the angle and the sharpening vector slightly change the microgeometry. The grit size of the abrasive wheel also has an effect. The distribution curves Rmax and S are close to the curves of the normal distribution for the knife.

The average *b* of the cutting edge and the parameters of the microrelief are determined.

To the study it is shown that electrocorundum grinding wheels are usually used for sharpening. Sharpening is conducted with the following characteristics: V of the grinder - 20 m/s; the stone is across the blade, the knife is in the running position; ∠ of sharpening is 170°. As the parameters of the microrelief and *b* of the cutting edge, the following are used: (1) Rmax; (2) Ra - the μ of profile deviation; (3) Rp - the max H of edge; (4) r - the average radius of the protrusion; (5) h - the reference l; (6) Sm - the step of the microroughnesses; (7) a - *b* of cutting edge. Samples are examined by a microscopic system, including a microscope, a screen, a display, and a computer. J. O. Sharipov and S. V. Fedorov [15] show that the grain size and hardness of the grinder have a leading influence on the microgeometry of the blade. They emphasize the superiority of grain size = 6, 10, 12, and hardness M_1 and M_2 as the normative characteristics of the abrasive. Characteristics of h and a allow improving the finishing of the blade with *min* heat generation and hardening of the treated surface by riveting. Finishing one edge causes bending of the blade tip due to F*n* processing, which is important for small ∠ of sharpening. Two-way processing improves microgeometry characteristics.

The authors agree with the authors in [16] that the blade supporting curve is influenced by finishing and cubic boron nitride sharpening in the absence of the original curved section. On the second straight section h = f(ε) they are located higher for the blades, with a large S of contact. $K_{\text{supporting curve surface}}$ has the dynamics of modifications in a wide range. The experimental data demonstrate the decrease in the roughness of the cutting edge when finishing along one and two edges. Finishing on two edges reduces the parameters H of the cutting edge by half. Close to finishing results are demonstrated by using circles made of cubic boron nitride, which have high cutting properties, and boron nitride HRC. This may have a certain significance in the formation of microteeth with zero transverse steps. Finishing on one edge is inferior in terms of the efficiency of cubic boron nitride to grinding.

M. N. Klimenko [17] believed that the effect of cutting the cutting edge with sharp teeth has a certain positive effect on the amount of cutting only in the initial (running-in) period of knife operation. Considering the influence of cutting-edge sharpness from the cutting force, M. N. Klimenko states that the approaches of researchers differ somewhat on this issue. However, the nature of the occurrence of the destruction effect and the magnitude of contact stresses in the cutting zone have been studied, in the opinion of the author, clearly insufficiently. During the research of cutting ability, it was established that it increases with increasing sharpness of the blade and decreasing sharpening angle, and has determined that this value is the reciprocal of the total cutting force. It was determined that the cutting ability of the blade by the ratio of the step of microroughnesses along the cutting edge to the height of microroughnesses, which is 2.5-3.0 in the initial stage of knife use and as a result of the durability period, this ratio equal to 10-11, while other parameters were not considered. In our previous studies, there were already given results of the cutting ability of knives depending on the main characteristics of the microgeometry of the blades. In this work, having given analytical arguments, we have shown the main factors affecting the cutting ability of lamellar knives.

5 Conclusion

The calculations performed show that the change in cutting ability is most noticeable during the transition from the running-in stage to normal operation.

The advantage of the obtained ratios for calculating the cutting ability of knives is consideration of the diverse characteristics of the blade microgeometry; reflection of the three main periods of operation of the cutting tool - running-in, steady-state period, blunting; the possibility of experimental determination when cutting in the $R_2 = const$ mode. The obtained analytical expressions allow optimizing the parameters of the microgeometry of the blades.

Nature of the destruction of material on the blade depends on the friction parameters and the contour angle γ of the microteeth. Microcutting is possible at an average probable value of $\gamma<45^0$; otherwise, the formation of a new surface occurs under conditions of elastic-plastic displacement due to repeated deformation of the material in the contact area increases in the number of chips and decreases in quality indicators. Resulting analytical relationships for the value of the cutting ability reflect the main stages of knife operation - run-in and steady wear – and allow experimentally determining this important operational characteristic. Because of optimization of cutting parameters in the period of normal operation, kinematic and geometric characteristics that provide the maximum value of the cutting ability of knives have been obtained.

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