E3S Web of Conferences **390**, 02010 (2023) https://doi.org/10.1051/e3sconf/202339002010
AGRITECH-VIII 2023

Contact interaction of blade microteeth with cut material of food half-finished products

Mukhabbat Saidova*, *Abror* Nematov, and *Bakhrom* Bafaev

Bukhara Engineering-Technological Institute, Bukhara, Uzbekistan

Abstract. The paper presents comprehensive research allowing to solve a scientific problem of great national economic importance. The authors describe the issues of interaction of the blade microteeth with the cut material of half-finished food products in order to improve the process of sliding cutting of food materials, considering the simultaneous penetration of the cutting wedge of the knife in the feed direction and the contact effect of the blade microteeth during its tangential movement. The high efficiency of sliding cutting can be ensured by an optimal combination of kinematic, geometric and microgeometric characteristics of the work members of cutting and knife grinding machines. The result of the work shows that when designing cutting machines, it is advisable to focus on the values of the slip coefficient, which ensures the separation of the half-finished product in the sliding cutting mode with minimal energy consumption.

1 Introduction

The main tasks that food industry is faced with are the intensification and optimization of technological processes, the introduction of new progressive types of equipment for rational processing modes that increase production efficiency, reduce energy costs and losses of raw materials, as well as improve product quality [1, 2].

Cutting is one of the technological ways of mechanical processing of various materials. Because of the difference in the physical-mechanical properties of a particular material, which affects the cutting process, there are various requirements on the modes and methods of cutting, as well as on cutting tools [3, 4].

Cutting with a blade and its variety, called sliding cutting, are mainly used for finished and half-finished products of the food industry. This type of cutting is also widely used in various sectors of the national economy, i.e. agricultural production, light industry, etc.

The theory of blade cutting is based on the works of V.P. Goryachkin [5], V.A. Zheligovsky [6], N.E. Reznik [7], A.I. Peleev [8]. In agricultural production, works of Ivashko A.A. [9], Egorova T.I. [10], Bosoy E.S., Sizov O.A. and others are also known, which made a significant contribution to the study of cutting processes of raw materials of plant origin. In various branches of light industry, the results of the research works of I.I. Kapustin [11], Maizel M.M., Lebedev I.I., Amirkhanov D.R., Bazyuk G.P. and others are widely used.

* Corresponding author: urinov1960@mail.ru

An analysis of the literature data shows that in most studies the main question is about the forces that arise when cutting various materials. With a known material to be processed under the initially selected conditions and cutting mode, only the subsequent force pattern that occurs on the working surfaces of the cutting tool ultimately determines the quantitative and qualitative indicators of the technological operation.

2 Methods

It is expedient to research the features of the contact interaction of the blade microteeth with the food half-finished product at the first stage based on the analysis of the movement in the material of a single microtooth under the action of given forces.

As a model of a microtooth, a cone with a spherical apex with the following angular and linear characteristics was accepted: angle at vertex γ, rounding radius ρ, circle diameter d in the section located at the working height h_p of the microtooth:

$$d = 2\sqrt{2\rho h - h^2} \quad \text{at} \quad h \leq (\rho - \rho \sin\gamma)$$

$$d = 2tg\,\gamma\left(h + \frac{\rho}{\sin\gamma} - \rho\right) \quad \text{at} \quad h > (\rho - \rho \sin\gamma)$$

The value of h_p depends on the kinematics of cutting and determines the contact zone in the form of a curved surface of a conical shape.

In order to simplify, we replace the spatial force interaction with a plane one. Let us select an element in the material adjacent to the surface of the microtooth at point *X* (Fig. 1.a). The microtooth acts on this element in the normal 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 force N_1 and the friction coefficient *f*:

$$F_1 = fN_1 \tag{1}$$

The forces F_1 and N_1 N1 give the resultant S_1, which expresses the impact of the microtooth on the material. It forms some angle ε_0 with the vector $\overline{N}_1$, and $tg\varepsilon_0 = f$. Vector S_1 forms an angle ψ with the direction of sliding of the blade, called the angle of action

From the equilibrium conditions, at the point *X* we have:

$$\begin{aligned} F_1' &= P_1 \sin\varepsilon_0 - Q_1 \cos\varepsilon_0, \\ N_1' &= P_1 \cos\varepsilon_0 - Q_1 \sin\varepsilon_0 \end{aligned} \tag{2}$$

where: N_1' and F_1' are respectively the normal and tangential reactive forces of the impact 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; Q_1 is the force of lateral compression of the material at point *X*, acting normally to the direction of sliding; ε_0 is current angle for the upper contour of the microtooth. After substituting (1) into (2) and transformations, we obtain a formula for determining the angle of action ψ:

$$tg\,\psi = \frac{tg\,\varepsilon_0 - f}{1 + f \cdot tg\,\varepsilon_0} \tag{3}$$

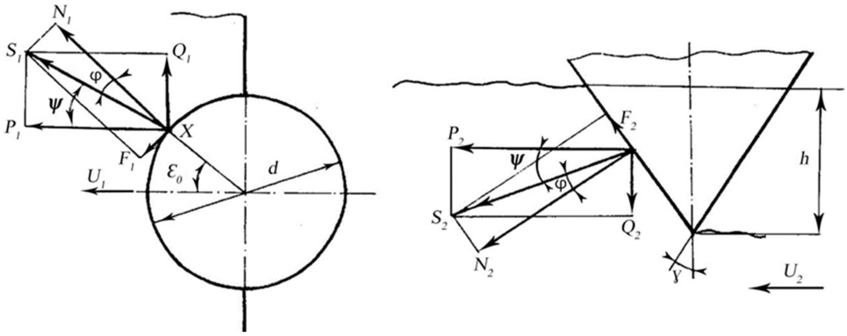

Fig. 1. Power circuits for a single microtooth: a - in the horizontal plane; b-in the vertical plane.

If $tg\varepsilon_0 = f$, then the angle ψ becomes equal to 0, this means that the force Q_1 is also equal to 0. If $tg\varepsilon_0 < f$, then the angle of action ψ changes sign to negative. Physically, this means that the force Q_1 began to slow down the material element at point X, which, being compacted, begins to move along with the microtooth in the direction of sliding. The condition under which the material shifts in the sliding direction of the counterbody is the boundary condition for the transition from elastic-plastic contact to microcutting [12].

3 Results

The microcutting zone is located in the central part of the microtooth between two symmetrically located boundary points, in which the angle $\varepsilon_0 = arctgf$. Its width is equal to the length of the chord corresponding to the central angle $2\varepsilon_0$, that is

$$l = 2r_h \sin \varepsilon_0 = 2r_h \sin arctgf \tag{4}$$

Above this width, the material will be elastically-plastically pushed in both directions outside the microtooth contour.

Let us consider the system of forces (Fig. 1.b) acting on the material in the vertical plane, while replacing the curved surface of the microtooth in the microcutting zone with a flat one.

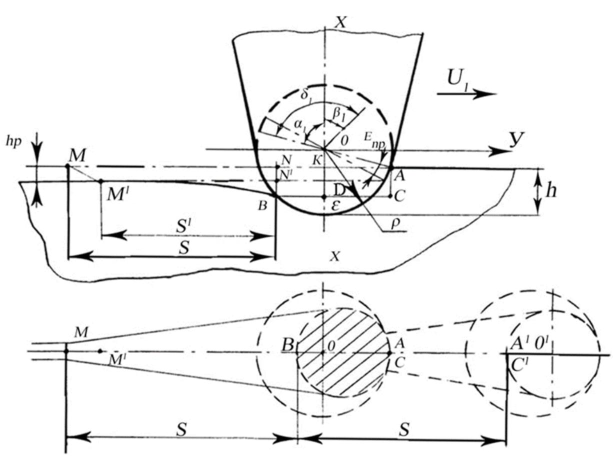

Fig. 2. Determining the possibility of interaction between adjacent microteeth.

When the microtooth moves in the direction of the vector $\overline{u}_1$, its working surface acts on the material with the forces P_2 and Q_2. Upon contact, a normal reaction force $N_1^{'}$ and a friction force $F_1^{'}$ arise respectively.

From the conditions of the balance of forces we have:

$$F_2^{'} = P_2 \sin \gamma - Q_2 \cos \gamma, \quad N_2^{'} = P_2 \cos \gamma - Q_2 \sin \gamma, \tag{5}$$

from these equations, if we substitute $F_2^{'} = fN_2$ and $tg\,\psi = \frac{Q_2}{P_2}$ into them, we obtain:

$$tg\,\psi = \frac{tg\,\gamma - 1}{1 + ftg\,\gamma} \tag{6}$$

As before, we note that at $tg\gamma < f$, the angle of action changes sign. In this case, self-braking of the material in the contact zone begins and it begins to move with a microtooth. Since the positive value of the angle of action ψ was chosen based on the condition that the deformable material moves relative to the microtooth in the direction from the base to its top, i.e. rises with a microtooth, then the value of the angle γ, at which the angle ψ changes sign to negative will determine the boundary conditions for the transition from elastic-plastic deformation to cutting.

If we take f=1, then we get the limiting angle $\gamma = 45^0$. At $\gamma \leq 45^0$, the destruction of the material by a microtooth (microcutting) will occur. Otherwise, the material will rise with a microtooth, i.e. undergoes elastic-plastic displacement. In this case, the formation of a new surface will be performed with repeated deformation of the friction track, leading to an increase in the number of edges and a decrease in quality indicators.

Hereby, in case $\gamma < \gamma_{np}$ the material is cut by the conical part of the microtooth. Therefore, the deformation of the material is possible only with a part of its spherical vertex where the variable angle is $\gamma > \gamma_{np}$. This zone is characterized by pressing the material under the spherical vertex and stretching it in the direction of the tangential movement of the cutting tool. Significant smaller values of σ_s in tension can lead to the fact that in the absence of conditions for microcutting, the material is destroyed not by a growing crack from the initial microcut, but due to rupture under the action of tensile stresses σ_z, reaching the value of σ_s in tension.

Depending on the value of S_m, cutting modes and rheological characteristics of the material being cut, it is possible to determine the length S of the microsection where the material is restored. If S_m>S, then the subsequent microtooth interacts with the undeformed material and therefore the difference between the kinematic height h and working height h_p of the microteeth is minimal. This also indicates that adjacent microteeth have practically no mutual influence.

Under the assumptions made, the microtooth will encounter the material along a spherical segment, the base of which (Fig. 2) is a circle of diameter AB. The central contact angle will be equal to the sum of the front α_1 and rear β_1 angles: $\delta_1 = \alpha_1 + \beta_1$. We assume that the length of the recovery zone S is proportional to the size of the segment BC, i.e. the maximum length of the projection of the contact zone on the horizontal plane. The cut $S^{'}$ takes into account the fact that the material at the working height h_p is cut by the front surface of the microtooth.

The material beyond point B will be stretched. If we assume that the stretching of the volumes of the material to the critical value $\overline{\mathrm{BC}}'$ corresponds to its destruction (rupture), then the length of the recovery zone is equal to the length of the segment $\overline{\mathrm{BC}}' = S$

The relative elongation at rupture is determined by the expression:

$$\varepsilon = \frac{\overleftarrow{BC'} - \overleftarrow{BC}}{\overleftarrow{BC'}}$$

$$\overleftarrow{BC'} = \left(1 + \varepsilon_p\right)\overleftarrow{BC} \tag{7}$$

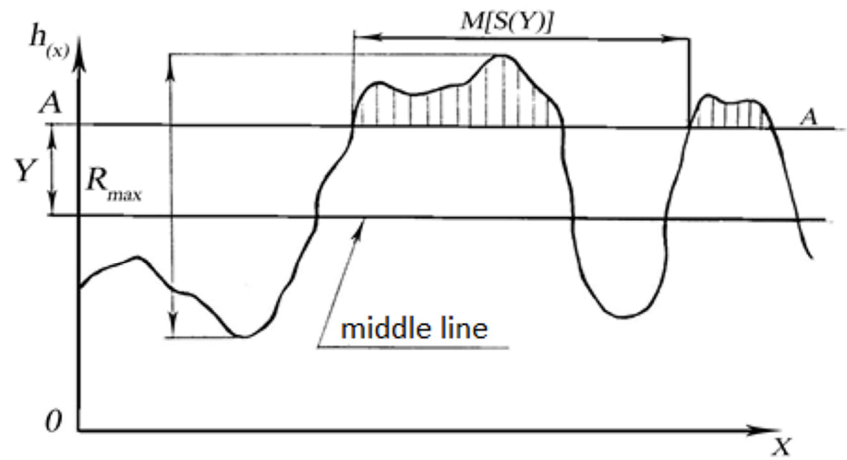

Fig. 3. Profilogram of cutting edge as a realization of a random function.

From the considered triangles ΔABC and ΔAOK after transformations, we can obtain:

$$\overline{BC} = \rho \sin \beta_1 + \sqrt{2\rho h - h^2} \tag{8}$$

Substituting this expression into (5), we get:

$$S = (1 + \varepsilon_p)\left[\rho \sin \beta_1 + \sqrt{2\rho h - h^2}\,\right] \tag{9}$$

In order to find the angle, it is advisable to use the method of Kapustin I.I. [11], who determined the relief angle from the expression:

$$tg\,\beta_1 = tg\left(\beta_2 \frac{\varepsilon_p}{1 + \varepsilon_p}\right);$$

where: β_2 is the angle of inclination of the tangent to the curved surface of the material being processed $\beta_2 = \pi / 2 - \alpha_0$;

α_0 is the angle between the vertical and the resultant cutting force R. Then

$$\beta_1 = \left(\frac{\pi}{2} - \alpha_0\right)\frac{\varepsilon_p}{1 + \varepsilon_p} \tag{10}$$

The value of the angle a_0 depends on the ratio between the components R_1 and R_2 of the total cutting force. As experimental data show [13], in sliding cutting of food materials, the ratio R_1/R_2 is close to 1, therefore $\alpha_0 = 45^0$, and expression (8) will take the form:

$$\beta_1 = 45^0 \frac{\varepsilon_p}{1+\varepsilon_p} \tag{11}$$

Substituting (9) to (7), we have:

$$S = (1+\varepsilon_p)\left[\rho \sin\left(45^0 \frac{\varepsilon_p}{1+\varepsilon_p}\right) + \sqrt{2\rho h - h^2}\right] \tag{12}$$

The longitudinal step of the blade microrelief is determined from the condition:

$$S_m = S' + l_1 + l_2, \tag{13}$$

where: l_1, l_2 are the length of the contact zone of the microtooth with the material along the front and back surfaces, respectively.

The sum (l_1+ l_2) is equal to the length of the segment $\overline{BC}$ and is determined by expression (6).

Approximating the curve of the surface of an elastically recovering material by a straight line BM, we consider that the length of the section is approximately equal to the length of the segment $\overline{M'N'}$. Then from the similarity ΔMNB and $\Delta M'N'B$ and we have:

$$\frac{\overline{MN}}{\overline{M'N'}} = \frac{\overline{NB}}{\overline{N'B}} \quad \text{or} \quad \frac{S}{S'} = \frac{\overline{NB}}{\overline{N'B}} \tag{14}$$

Hence $S' = S\frac{\bar{N}'\bar{B}}{\bar{N}\bar{B}}$

From Fig. 2 we can see that

$$\bar{N}\bar{B} = h - \overline{\mathrm{DE}}; \bar{N}'\bar{B} = h - \overline{\mathrm{D\,E}} - h_p$$

Since

$$\overline{\mathrm{D\,E}} = \bar{O}\bar{E} - \overline{\mathrm{OD}} = \rho(1-\cos\beta_1), \text{ then}$$

$$\bar{N}\bar{B} = h - \rho(1-\cos\beta_1) \tag{15}$$

$$\bar{N}'\bar{B} = h - \rho(1-\cos\beta_1) - h_p \tag{16}$$

Substituting the values (7), (14) and (15) into expression (13) and performing the necessary transformations, we obtain

$$S' = (1+\varepsilon_p)\left[\rho \sin\beta_1 + \sqrt{2\rho h - h^2}\right] \cdot \left[1 - \frac{h_p}{h-\rho(1-\cos\beta_1)}\right] \tag{17}$$

After substituting the values (6) and (16) into expression (12) and performing transformations, according to the expression for calculating the recovery zone:

$$S = \left[1 + (1+\varepsilon_p)\left[1 - \frac{h_p}{h-\rho\left[1-\cos\left(45^0\frac{\varepsilon_p}{1+\varepsilon_p}\right)\right]}\right]\right] \cdot \left[\rho \sin\left(45^0 \frac{\varepsilon_p}{1+\varepsilon_p}\right) + \sqrt{2\rho h - h^2}\right] \tag{18}$$

At the values $h \le \rho\left[1 - \cos\left[45^0 \frac{\varepsilon_p}{1+\varepsilon_p}\right]\right]$ expression (17) loses its physical meaning, since there will be no cutting. In this case, the sliding of the microtooth over the material is observed. The same happens if $h \le \rho\left(1-\cos\varepsilon_{np}\right)$

Table 1. Calculation table of the dependence of the length of the recovery zone.

h **[mcm]**	***S*** **[mcm]**		
	ε_p=0.1	**ε_p=0.3**	**ε_p=0.6**
10	30.9	35.1	39.3
20	28.5	32.6	36.9
30	22.8	26.1	29.8

Calculations carried out at ε_{np}=45^0 and ρ=20 mcm (microns) how that the length of the recovery zone increases with increasing ε_p and decreases with increasing h (Table 1). The calculated values of S are significantly lower than the real values of the longitudinal pitch recorded on the profilograms (Fig. 3.) of both sharpened (T = 0) and working blades. This gives foundation to conclude that under normal conditions of sliding cutting, the microtooth of the blade does not mutually influence each other.

The movement of a microtooth in the microcutting mode leads to the formation of an initial microcut in the material, the depth of which is equal to the working height of the microtooth.

The difference between the kinematic and working height of the microtooth is the height of the material layer pressed down under the spherical top of the microtooth during its tangential movement:

$$h - h_p = \rho(1 - cos\,\gamma_{la}), \tag{19}$$

where: h is the kinematic height of the microtooth;

$$h = \frac{S_m}{K_c + tg\,\theta / 2}; \tag{20}$$

h_p is working height, $h_p = l_0 = \frac{aE_{din}}{8\sigma_S}$;

γ_{la} iscritical angle, $\gamma_{la} = arctgf$,

ρ is radius of the spherical vertex of the microtooth.

The kinematic condition for the destruction of the material by the front part of the microtooth can be in the form:

$$h > \rho(1 - \cos\gamma_{la}), \tag{21}$$

Otherwise, instead of forming a new surface, the microtooth vertexes rub against the material, and the corresponding slip coefficient satisfies the condition:

$$K_C > \frac{S_m}{\rho(1 - \cos\gamma_{la})} - tg\frac{\theta}{2}. \tag{22}$$

From formula (18) it is possible to determine the kinematic height of the microteeth:

$$h = \frac{aE_{din}}{8\sigma_S} + \rho(1 - \cos\gamma_{la}) \tag{23}$$

The slip coefficient that provides such a height of the microteeth must satisfy the condition:

$$K_C^{\max} < \frac{S_m}{aE_{din} / 8\sigma_S + \rho(1 - \cos\gamma_{la})} - tg\frac{\theta}{2} \tag{24}$$

The condition for the localization of the destruction of the material in the zone of the microteeth of the blade:

$$R_{\max} > h \tag{25}$$

Considering formula (19) and the fact that $tg\frac{\theta}{2} = \frac{2R_{max}}{S_m}$, we can obtain an expression for calculating the value that satisfies condition (20).

$$K_C^{\min} \geq \frac{S_m^2}{R_{\max}(S_m + 2R_{\max})} \tag{26}$$

Table 2 is presented as a numerical example illustrating the nature of the influence of the parameters of the microgeometry of the blade of the circular knife of the MPGU-300A machine, which change during the operation of the cutting tool, on the values of the slip coefficient that ensure the fulfillment of the kinematic condition (23) and the localization condition (25).

Table 2. Changing the parameters as the knife is blunted.

T [hours]	0	0.5	2	6	12
ρ [mcm]	1	1	3	10	20

S_m [mcm]	100	50	150	300	500
R_{max} [mcm]	20	10	20	30	40
$K_C^{\min}$	3.6	3.6	5.9	8.3	10.8
$K_C^{\max}$	300	160	150	100	84

4 Discussion

The data in Table 2 show that as the knife becomes dull, the range of possible variation of K_c decreases from 83.3 to 78, i.e. almost 11 times. Sharp knives (T=0-0.5 h) ensure the destruction of the material by the front face of the microteeth even at high slip coefficients (K_c=150-250). However, during the further operation of the knife (T>2 h), a change in the parameters of the microgeometry of the cutting edge necessitates a significant reduction in the limit value K_C^{max}. At the same time, for fulfillment of the condition of localization of destruction in the zone of microteeth K_C^{min} must be increased, as can be seen from Table 2, by almost three times.

5 Conclusion

Calculations show that the use of work members that realize values of slip coefficients close to K_C^{max} is energetically unfavorable and therefore, when designing cutting machines, it is advisable to focus on values K_C^{min} that ensure the separation of the half-finished product in the sliding cutting mode, but with minimal energy consumption.

References

1. A. Yu. Karpachev, S. V. Martynov, D. I. Polyakov, Bulletin of Mechanical Engineering **4**, 2-26 (1991)
2. Nasullo Urinov et al, IOP Conference Series. Materials Science and Engineering **734(1)** 012073 (2020)
3. Nasillo Faizilloevich Urinov, Lyudmila Vladimirovna Dubrovets, Pedagogy journal **3.2**, 21-26 (2022)
4. Nasillo Fayzilloevich Urinov, Mukhabbat Khamroevna Saidova, Journal of Architectural Design **11**, 18-22 (2022)
5. V. P. Goryachkin, *Collected works in 7 volumes* (Selkhoziz, M., 1940)
6. V. A. Zheligovsky, *Experimental theory of blade cutting.* Proceedings of Moscow Institute of Mechanization and Electrification of Agriculture **9** (1940, M.), pp. 32-48
7. N. E. Reznik, *The theory of blade cutting and the foundation for calculating cutting devices* (Mashinostroenie, M., 1975)
8. A. I. Peleev, M. N. Klimenko, The meat industry of the USSR **5**, 45-47 (1966)
9. A. A. Ivashko, Tractors and agricultural machines **2,** 34-37 (1958)
10. T. I. Egorova, *Research of the influence of the parameters of the cutting tool on the process of blade cutting* (M., 1949)
11. I. I. Kapustin, *Cutting and cutting tools in the leather and footwear industry* (Gizleprom, M., 1950)
12. I. V. Kragelsky, *Friction and wear* (Mashgiz, M., 1968)

https://doi.org/10.1051/e3sconf/202339002010

13. H. S. Mustafaev, *Improving the efficiency of disk-type machines for cutting food materials* (1991, M.)