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Physical model of the process of sliding cutting for innovative development of sustainable systems of agrarian-and-food production

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Abstract. Sliding cutting is considered the most advanced way of material cutting due to its technological efficiency. Its implementation is in focus in the practice of cutting machines designing. Sliding cutting is the most promising type of cutting for elastic-viscous-plastic food materials. The article covers the operation process of the fracture micromechanism during sliding cutting, presents the developed physical model of the formation of a new surface as a result of the simultaneous introduction of the cutting edge and the contact interaction of the working surfaces of the blade with the material being cut. In the conclusion the authors prove that the stretched zone of the material is located directly under the blade and accessible to the action of microteeth, which increases the efficiency of sliding cutting.

1 Introduction

The innovative food industry has to be developed based on accelerating scientific-technological progress in the sector, optimizing the consumption and production of food products, strengthening the coordination between food and agricultural enterprises and organizations, increasing production efficiency in a market economy, and improving structural and investment policies.

Cutting is defined as a technological process of material processing by separating it into parts under the pressure of a cutting tool [1]. The cutting of food raw materials is a type of destruction of materials in general and is distinguished by the peculiarities of the technological process, which consists in separating the product by the cutting tool into parts with certain, predetermined dimensions and quality of the cut surface.

V.P. Goryachkin [2] first drew attention to the fact that cutting as a technological operation can be carried out in two ways: when moving the cutting tool only in the direction normal to the blade, or when moving it in two mutually perpendicular directions: normal to the blade and parallel to him. In the first case, the cutting process is called normal cutting, or chopping, in the second is called sliding cutting [3, 4].

The knife pressure will be the highest during normal cutting. This is undesirable in a number of cases, and sometimes it is unacceptable. Almost all such cases relate to the cutting

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of elastic-viscous-plastic food materials, which, under high pressure, can receive a deformation that is unacceptable under the conditions of the technological process.

Considering the obvious technological efficiency, sliding cutting is examined as the most advanced as the most advanced way of material cutting, the implementation of which is in focus in the practice of cutting machines designing. Researchers in various sectors of the national economy conclude that sliding cutting is the most promising type of cutting for elastic-viscous-plastic materials. Therefore, this type of cutting is extremely widespread in various sectors of the agro-industrial complex. Being an integral part of many technological processes, it is used in tillage, harvesting and processing of agricultural and livestock products [3; 5]. In many branches of the food industry, operations related to cutting raw materials, semi-finished and finished products total up to 70-90% [6-9].

2 Methods

Decisive technological advantages of sliding cutting predetermined keen interest in it in various sectors of the national economy that process raw materials of plant and animal origin. Despite the abundance of diverse studies, fundamental connections and relationships that allow building an integral physical model have not yet been established. The choice of the model class in each specific case depends on the level of a priori information about the mechanics of the system under consideration. Most probably, for the physical modeling of sliding cutting of food materials, it is advisable to focus on the combined “empiric-mechanical” method [10-14].

Modeling sliding cutting is based on the following points. It was assumed that classical solutions obtained for isotropic materials and macroobjects can be used to describe deformations and stresses under the blade. Since the real shape of microteeth can differ significantly from the accepted models, it is necessary to use both a deterministic and a stochastic approach in modeling. Due to the limited accuracy of the initial data on the microgeometry of the cutting edges, approximate solutions should be considered acceptable.

Physical foundations of sliding cutting are complex and impossible to understand based on existing ideas about the destruction of the material due to its crushing by the edge of the blade. The mechanism of destruction of the material during sliding cutting can be represented because of the simultaneous introduction of the cutting wedge and the contact interaction of the microteeth of the blade with the material being cut. At the same time, it is expedient to consider the process under study at two levels, i.e. on a macroscale (sample volume or workpiece) and on a microscale (surface contact layer).

3 Results

In penetration of the cutting wedge in the direction of the velocity vector, a complex deflected mode is created in the volume of the material. The stress field created in an elastic medium by the cutting wedge of the tool corresponds to the Boussinesque field [15], the trajectories of the main stresses of which are shown in Figure 1a.

The main stresses σ_1 and σ_3 act in the symmetry plane passing through the immersion axis and are tensile and compressive, respectively. When considering a plane problem, σ_2 component (circumferential stress) is equal to zero. The maximum for σ_1 is observed at the action angle $\psi = \pi / 2$. The distribution of the main normal stresses can also be represented using contour lines (lines of equal stresses), on which the value of the average contact pressure is taken as a unit stress $q = R / \pi a^2$.

In the sequel, as the cutting wedge penetrates, despite the general elastic nature of the interaction, local plastic deformation occurs at the point of contact between the blade and the material (Fig. 1b), due to the impact of the blade and which is the source of the initiation of macrofracture, i.e. the initial microcrack. The legitimacy of using the term “crack” is confirmed by the studies of G.M. Bartenev [16], who showed that the mechanism of destruction of elastomers is similar to that in the destruction of brittle bodies, and is a direct rupture of bonds during the growth of cracks. Here, the results of the experiments of M.I. Kornfeld can also be pointed [17], who established that in the case of a sufficiently high load application rate, even low-viscosity liquids can be destroyed by cracks.

With a further increase in the load, the initial microcrack, acting in the field of tensile stresses, begins to develop and subsequently grows into an axial, so-called median crack, located in the plane of axial symmetry (Fig. 1b). The median crack grows downward along the axial stress σ_3 axial stress trajectory orthogonally to the σ_1 stresses. The interaction of stress fields σ_1 and σ_3 contributes to the stable direction of crack development. Compressive stresses σ_3 are applied along this direction. Since the crack grows under the action of tensile stresses σ_1 normal to its edges, compressive stresses σ_3 do not prevent it from moving in the right direction. If the crack begins to turn to the side, then the stresses absorb it. When a crack invades a compressed zone, the elastic fracture energy that promotes its development is quenched in the opposite elastic compression field, and the fracture stops. Therefore, the crack can only develop in the main direction.

Upon transition to the elastoplastic-loading scheme, the stress field corresponds to the so-called Hertz contact [16,18]. The trajectories of the principal stresses of the Hertz field and the lines of equal principal stresses in the plane of the axial section are shown in Fig. 1c.

Inside the contact area, the main stresses are compressive and similar in rate. The high hydrostatic pressure within this zone eliminates the possibility of fracture occurring. Calculations show that σ_1 becomes tensile only at a depth equal to the length of the contact area. As the load increases, the stresses increase in proportion to the average contact pressure. When the maximum shear stresses reach a certain value, plastic deformation, i.e a dark zone is initiated in the material (Fig. 1d). An increase in load leads to an expansion of the plastic zone, at the base of which a median crack appears. The nature of the load application and the properties of the cutting object have a significant impact on the distribution of stresses near the contact. The difference concerns not only the shape of the stress trajectory, but also, importantly, the rate and sign of the latter. An analysis of the differences in the penetration of the knife according to the elastic and elastoplastic schemes shows that elastic deformation ensures the presence of tensile stresses along the entire contact axis.

Thereby, the mechanism of destruction during chopping cutting is associated with the introduction of a cutting wedge and the creation of a certain deflected mode at the stage of pre-compression. When the limiting values of σ_s are reached, such an action can independently provide the formation of a new surface, as a rule, due to significant deformation and transition of the contact from an elastic to an elastic-plastic state.

As the cutting wedge deepens in the contact zone, due to the action of σ_1, the conglomerates of macromolecules that form the basis of the microstructure of the materials under study are stretched and torn one after another. The rupture of individual conglomerates occurs in random places; therefore, after stress relief and the restoration of the size of most macromolecules, protrusions and depressions appear on the cut surface, which together form a rough uneven surface.

In sliding cutting, just as in the first case, the introduction of a wedge-shaped knife leads to the appearance of tensile stresses (contours) in a certain direction, which tend to straighten the bent volumes of material and disappear. A microtooth moving in a tangential direction perpendicular to the contour first creates a notch-stress concentrator, where all the energy of the elastically deformed volume is concentrated on a small area of the material. Thereby, the initial notch is the focus of destruction and is created in this case not due to high contact pressures and the formation of a plastic zone, but due to micro-impact of the cutting edge elements.

This shows that the action of the micromechanism of destruction is possible only with sliding cutting, when the microteeth of the blade act on the stretched zone of the material, which ensure the formation of microcracks in the material exactly along the line of movement of the blade. The presence of tensile stresses σ_1 and the initial micronotch lead to a rapid rupture of the material because of the propagation of fracture cracks.

When a microtooth moves in the field of its active influence along the motion front, a multicomponent force situation develops, where compression, separation or shear deformations act. The action of a complex field of contact stresses, in the formation of which plays a significant role in the friction process, causes a contact deformation of the material, which determines the dimensions of the contact area and, accordingly, the stress state.

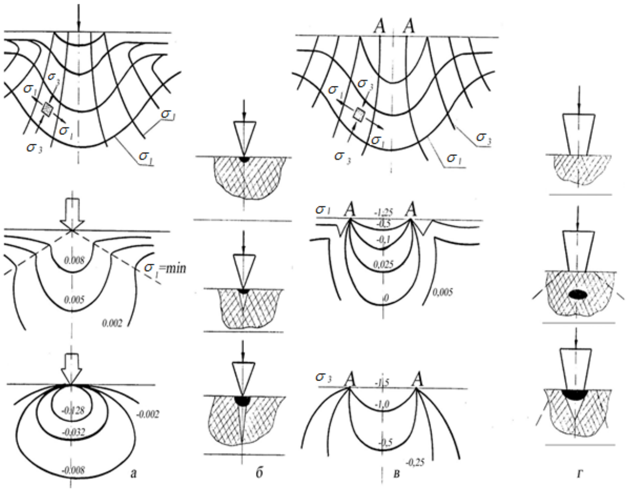

Fig. 1. Elastic and elastoplastic stress field in the cut material.

The tangential movement of the microteeth of the blade creates an area of surface tensile deformations. At the preliminary stage of deformation, when the friction coefficient has not yet reached a critical value, the action of the macrofracture mechanism is localized in a thin surface layer of the material and does not affect the overall deflected mode of the material.

With small penetrations, the formation of waste and crumbs is possible due to adhesive forces (Fig. 2), when the material sticks to the spherical tip of the microtooth, breaks along the slip line and stretches in the direction of movement. Subsequently, a subsequent microtooth separates the formed wire-edge. With an increase in the working height of the microtooth, the friction force increases due to the deformation interaction. An increase in contact loads ensures the transition from elastic and plastic contact to microcutting.

Thereby, the tangential load that occurs in the contact areas during the sliding of the microteeth system significantly changes the nature of the deformation of the surface layers of the material. The sliding motion of the knife contributes to the emergence of areas of tensile deformations behind the moving microteeth, which, with increasing friction, can merge with deep areas of tensile deformations created by introducing a cutting wedge in the direction of the vector u_2.

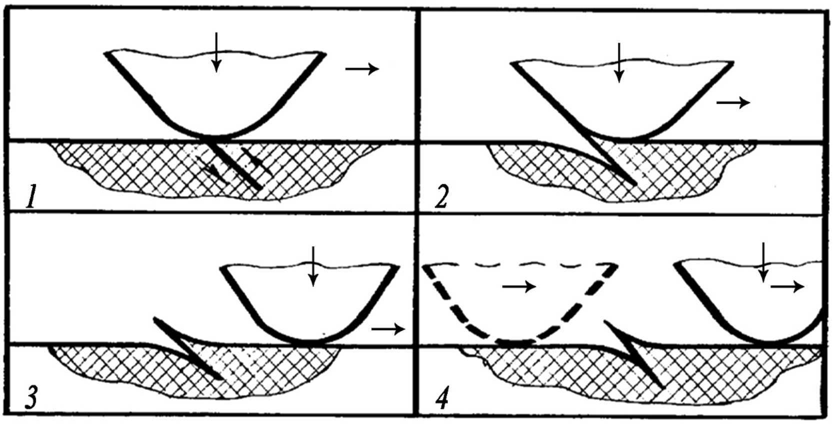

Fig. 2. Scheme of crumb formation under repeated influence of microteeth.

In the case of deformation according to the elastoplastic scheme, the surface to deep zone of tensile deformations are independent and are separated by a certain zone of compressive deformations (Fig. 1d), which prevent the propagation of a micronotch during the interaction of a microtooth and material. Here, even independent simultaneous destruction of the material in the surface layer and in the volume of the workpiece (sample) is possible. During elastic deformation, the most probable is the intensive formation of a new surface, since in this case the zone of tensile deformations continuously propagates from the surface to a relatively large depth.

4 Discussion

Mechanisms of contact fracture, shown in the physical model of sliding cutting (Fig. 3), correspond to different scales, and the role of each of them may change depending on the initial factors.

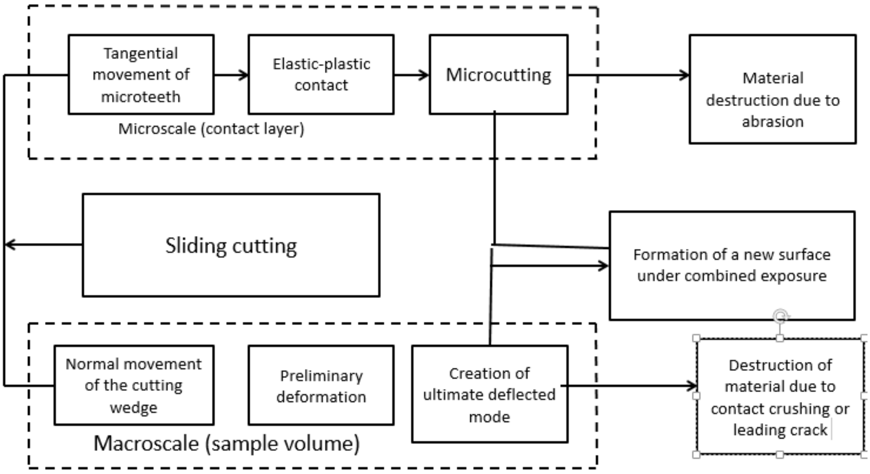

Fig. 3. Physical model of sliding cutting.

The impact of microteeth at the stage of preliminary deformation does not lead to the formation of a new surface due to the insufficient value of normal forces. The limit of preliminary deformation is determined by the nature of the contact and the state of stress of the processing object. The formation of the initial micronotch is carried out after the successive transition of elastic contact into plastic contact and then into microcutting, which subsequently, against the background of tensile stresses σ_1, initiates the macroscale formation of a new surface. Otherwise, the predominance of microscale processes without the presence of the limiting deflected mode in the bulk of the material will lead to the formation of recyclable waste in the form of chips and shavings.

Creation of a certain deformation scheme and contact conditions, most probably, is possible due to the appropriate preparation of the half-finished product for cutting, holding in time, cooling, varying the recipe or by changing the geometry of the cutting tool and cutting modes.

If a tensile stress field is not created in the volume of the material during the introduction of the cutting edge, which can occur with a relatively high rigidity (hardness) of the processing object, then the sliding cutting method is inefficient. This shows the scope of the process under study, which is, processing of highly elastic, and low-strength materials with a pronounced stage of preliminary deformation.

5 Conclusion

The formation of a new surface is presented in the developed physical model as the simultaneous introduction of the cutting edge and the contact interaction of the working surfaces of the blade with the material being cut. With an elastic preliminary deformation scheme, the stretched zone of the material is located directly under the blade and is exposed to microteeth, which increases the efficiency of sliding cutting. In the elastoplastic scheme, the microteeth work in the area of the compressed compacted material, which hinders the formation of a new surface and leads to a significant deformation of the processing object.

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