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THEORETICAL RESEARCH REGARDING THE CUTTING PROCESS

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Abstract: *This paper presents a theoretical study about cutting process of vegetable products. Theoretical study is performed taking into account the following simplifying assumptions: the material is an elastic surface that has unlimited ability to deform in a transverse direction in proportion to the thickness of the blade; cut material is in constant contact with the edge and the inclined faces of the knife; the tension generated in material mass is proportional to material deformations. In order to achieve the cutting process, is necessary that between the edge of the blade and the material that is going to be cut, there must be a relative movement, with a certain speed in relation to the material being cut, the knife can execute moves in two directions: normal and cross. For the choice of shredding mechanism and hence the type of shredding machines, is necessary to take into account the request states developed by the cutting organ in the material mass.*

Keywords: *crushing by cutting, elasticity modulus, deformation, resistance to cutting.*

1. INTRODUCTION

The behavior of solids subjected to grinding is very different, this fact is due to the influence of numerous factors involved in carrying out the cuts of the shredding operation. Cutting body has the shape of a wedge whose cutting edge and side surfaces interact with the material subjected to the cutting operation. In order to achieve the cutting operation, the cutting edge of the knife is pressed against the surface of the material from the contact area resulting a corresponding deformation; the mass of material develops a state of the work space, characterized by the amount of stresses normal σ and tangential τ. The normal tamping stresses produce structural elements of the material requested and tangential tensile stresses tend to move relatively foregoing. Deformations caused by these efforts, oppose connecting internal forces. The existence of intracellular liquid and gaseous phases produces a change in body mass distribution efforts σ and τ, because these phases do not undertake efforts than normal. When a mass of material points in contact with the blade, unified effort tangential value exceeds the shear strength, destroys the integrity of the material and cutting knife penetrates the mass of material, cutting taking place. Cutting character is dependent on structural and morphological characteristics of the material.

As the force action increases, the requested material deformation and the stress of its mass has a corresponding increasement.

2. MATERIALS AND METHOD

2.1. Crack propagation during shredding operation by cutting

Acting on material with a compressive force in its mass develops a state of efforts and as a result its surface will deform.

The cutting process can be divided into two stages:

- A first step, when under the action of the acting force on the cutting edge occurs the compression and the elastic deformation of the surface of the material and its cell tissue. The models developed by Pitt (1982) [8] and Pitt and Chen (1983) [9], the request compression causes lateral extension of cells due to the incompressibility of intracellular fluids, assuming that it does not move outside the cell, the cell volume remaining constant during deformation, it leads to a more intense application of the cell walls which are transverse relative to the direction of the directed force than the direction of the force. The observation plane transverse to the direction of deformation, the cells located in this plan increase its size, action that is confirmed by experimental observations of his Zdunek and Umeda (2006) [13] performed on potatoes and carrots by using a laser microscope. Apples cellular tissue differs from that of potatoes and carrots by the much higher number of intracellular spaces, with about 20%. In case of apples, the spaces are filled with gas, which is easily compressible. During deformation, joined cells may expand freely in these areas and in this case, reduces the volume gaps. Therefore, in the transverse plane of the 2D deformation cell size increases and decreases the size of the spaces [2].

- the second stage, when the force exceeds a critical value, reaches a maximum and the material will deform plastic, cellular tissue is destroyed and cause the release of cellular juice, destroys the integrity of the material, so the knife is penetrating the mass of material.

Depending on the morphological structure of the material, cutting is done with or without cause, bad crack in the mass of material. Cracks propagate rapidly and branches, the direction of the blade surfaces having an irregular shape again obtained. The amount of effort invested in the first phase of the material depends on the initial state (humidity) and for the second phase depends on the native structure of the material.

The relationship between the mechanical properties and cellular structure of the plant products attracts interest concerning the economic point of view. Food processors are trying to reduce losses due to cracking or breaking during cutting of food and the amount of energy required to be invested in the cutting process is minimal. Cutting the plant material is carried out with the purpose of giving the finished product specific characteristic shapes and sizes. Each initial plant entity product should be divided into smaller entities, often with debris and sites. The basic requirement imposed on the homogeneity of the finished product refers to the shape and mass. Fresh fruits and vegetables are cellular structures in which cell walls are biologically active elements, which contain a cytosol of water and dissolved salts (aqueous cytosol is the cytoplasm that fills cells). Intracellular membrane is semi-permeable, maintaining an internal pressure (turgor) higher than atmospheric pressure, thus achieving a prestressing of the wall. After harvesting, tissue water is lost gradually and the pressure inside the cell walls is reduced, the structure becomes soft and the measured force of resistance is higher according to tensile tests.

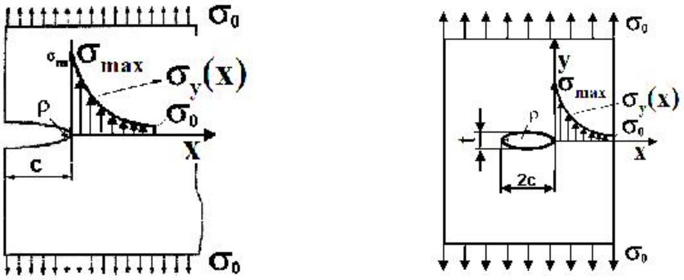
To obtain relevant information on the mechanical behavior of some of the most commonly used measurements are used tensile and loading/ relaxation tests. By initial request of material with increased effort, initially it deforms elastic and then plastic, as ultimately, to produce rupture caused by the formation of cracks that have the core around structural defects in material on a microscopic scale (cell). As a result, information can be obtained on the values of specific parameters: modulus of elasticity, yield strength, tensile strength, extent, tensile strength. Tensile tests conducted on the roots of carrots were published by Verlinden & al. (1996) that studied these parameters in detail but were not correlated with micro structural observations [11].

Through fresh tissue, with high turgor pressure, the action of blade knife will not cause rapidly deformation of cells, according to the amount of effort applied, the mechanical work done by knife being dissipated into the mass of material in the form of the deformation energy of the cells. Strain energy generated by the cutting blade remains focused on cutting edge at the end of the crack, resulting in a brittle rupture the cell wall type. A drop in pressure caused by the loss of turgor water content is one of the first manifestations of loss textural qualities. The flexibility gained by cellular structure allows the energy of deformation to be distributed in a larger volume of material. In many materials, deformation field is induced by the effect of compression, flexure generated and propagated through the layers; the deformation is a function of the modulus of elasticity value.

According to the strength of materials, for homogeneous materials, crack propagation condition is given by equality between elastic deformation energy per unit length and the energy required for the creation of two new surfaces with equal length to one unit. If a material is homogeneous and brittle, with elastic modulus E, with an elliptical crack length 2c existing unit (Fig. 1), the average unit σ_0 efforts necessary to break up the inter-crystalline and crack propagation is determined through the relationship:

$$\sigma_0 = \left[\frac{E \cdot \gamma}{c}\right]^{\frac{1}{2}} \tag{1}$$

where γ is the surface energy of the material.



a. end rift *b. material rift*

Figure 1: Crack propagation scheme [11]

In case of vegetables, which have a cellular structure, γ is the energy required to break the cell wall or intracellular membrane, the dominant process that occurs with the highest probability in the two cases will be one of the lesser value.

For the use of the above relation, to the cutting conditions of vegetables with their own cell structure, in order to take into account the viscosity properties of the liquid cell, released by cutting off the cells and the elasticity and plasticity of the cell wall or intracellular membranes in the relationship (2) is introduced the concept of specific energy of deformation γ_p, resulting the following relationship:

$$\sigma_0 = \left[\frac{E \cdot (\gamma + \gamma_p)}{c} \right]^{\frac{1}{2}} \tag{2}$$

Cell shape deformation and cellular fluid diffusion, that changes the mass distribution efforts of the state of plant material are taken into account through specific deformation energy γ_p, whose value is determined by plant material turgor pressure [11].

Equation 2 provides information on the conditions of fracture crack propagation; therefore it is necessary to consider how the stress is distributed longitudinally in the mass of material. Inglis's contribution to this mechanism model was to show that the stress at the crack tip σ_{max} is inversely proportional to the radius ° crack in the area and unified effort maximum value can be determined by the expression:

$$\sigma_{max} = 2\sigma \left(\frac{c}{\rho} \right)^{\frac{1}{2}} \tag{3}$$

Experimental research have shown that crack propagation occurs when $\sigma_{max} = \sigma_0$. This fact implies that when a material is subjected to the action of external forces, the amount of which plastic deformation occurs near the crack tip, the stress will be less concentrated locally. In this case, the material will be less prone to fracture propagation of a crack-type fracture.

In the process of cutting solid mass, it is supposed that the first crack in the mass of vegetables occurs when small defects are part of the microstructure, near the area where cutting edge body is acting.

Regarding the variation of the actuation force of the knife, experimentally determined, aiming simultaneously occurring changes in the process of formation and detachment of slivers, in case of a wedge-shaped knife, with cutting angle of $\delta = 45$ ° (fig. 2). By moving the mass of material, in the first phase of the process, the anterior surface of the cutter is pressing the material, the resistance offered by the material strength increases continuously from a minimum (Fig. 2 a). The sliver that emerges is subjected to a bending request by the anterior surface of the knife.

The maximum value of the resistance force (point D, fig. 2, a) is obtained when the crack occurs, then the resistance force decreases and the cycle is repeated. It points out that a wedge organ cutting, which

for low deep cut detaches from material mass continuous slivers, as the depth of the cut increases, the mass, cracks, as to the depths of cutting, the slivers (fig. 2 b) of the cracks are fragmented due to the table bending process is subjected to splinter. Each time, the crack grows from the top edge. If cracks are apparent or not depends on the circumstances how is produce the cutting process.

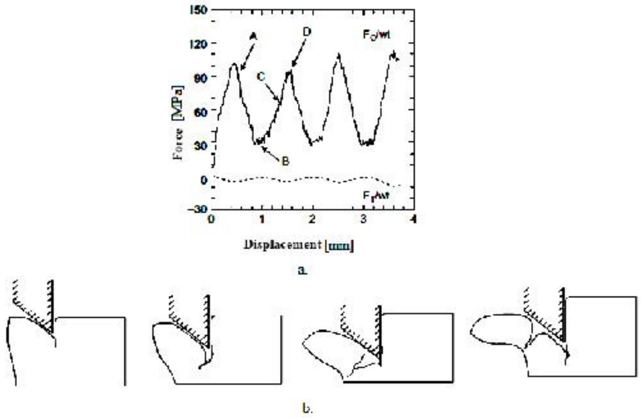


Figure 2: The variation of the driving force of the knife correlated with the detachment of the chip module [1]

The experimental measurements carried out by various authors have shown that the same material can behave differently during cutting based on the cutting angle of the blade, the depth of cut, cutting speed, the temperature of the material and the environment. A change in the value of cut resistance force during the movement of the knife during the cutting process allows obtaining information on the production mechanism of breaking the material. The mechanical properties are controlled by different processes dependent on the structure of the vegetable, as it relates to its biological origin.

For the choice of shredding mechanism and type of shredding machine, it is necessary to consider the request states developed by the bodies in the mass of material cutting.

Figure 3 shows the variation graph of the force F, which is experiencing a knife that is part of machine testing during the cutting operation, at a constant speed piercing the fibrous material with a knife bilateral sharpened, characterized by the angle of sharpening, which has a cutting edge disposed normal to the direction of displacement and which has a constant displacement speed for performing cutting by cracking.

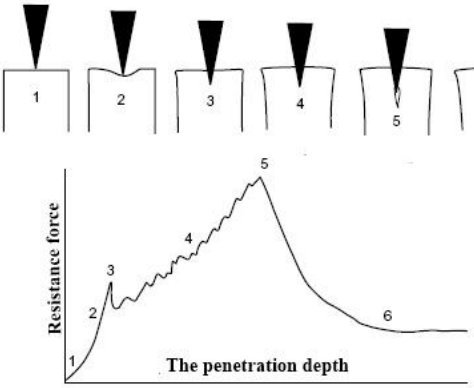


Figure 3: The main phases of the cutting process and the timetable of force variation resistance [12]

Specific phases of the cutting process, shown in Figure 3 are:

- when the cutting edge of the wedge is in contact with the material surface, the value of the cutting resistance force is equal to zero;
- when the wedge edge of the cutting surface of the material resiliently deforms, the deformation energy is accumulated in the mass of material in the form of elastic energy;
- status request generated by the cutting edge to overcome the resistance of the tissue reaches the maximum value, destroys the integrity of the product surface, the cutting knife penetrates the mass of material; this time the value of the resistance force is reduced by a certain amount, keeping subsequently increasing trend;
- As the knife penetrates further into the mass of material, the generated surfaces press on the knife area, so into the mass of material, the strain energy is transformed in part into elastic energy. The top of the variation curve indicates resistance to cutting cell walls;
- The accumulated elastic energy equals the potential energy characteristic to the resistance to cracking of the material, reason why before tip wedge crack is initiated, the moment the force is reduced;
- Crack propagation stabilizes; its propagation speed is equal to the speed of the trig. The force remains constant until material cutting.

Cut resistance force consists of the following components: power consumption for plastic deformation and elastic force that overcomes friction and adhesion forces, the force of disintegration consumed by the knife blade in the material structure.

The apparent deformation is dependent on the speed, for which the flow of fluid leaving the cells plays an important role.

Liquid flow cell depends on structural and morphological characteristics of the product. Apple tissue differs from that of potatoes and carrots by the higher number of intracellular spaces, with about 20%. In case of apples, the spaces are filled with gas which is easily compressible. During deformation, butted cells can freely expand in these areas and in this case, the volume of the gaps decreases. Therefore, in the transverse plane the 2D of deformation cell size increases and decreases the size of the spaces [2].

2.2. Influence of knife cutting angle

The analytical methods provide adequate values regarding the cutting forces [3], but most often are very complex and assumptions are not able to give information concerning some aspects like: coating, quality of cut surface, sliver features, etc. Koplev and others [4] [5] are among the first who investigated the cutting process. They highlighted the parameters that influence the cut resistance. Conducted experimental research highlighted the influence of fiber orientation and geometrical configuration of the cutting organ on cutting resistance.

In this work, Mkaddem A. and all [7], examined how specific force F_r varies, being created by the cutting edge and the total resistance specific force F_t at the drag of the knife, according to the values of the cutting angle (fig. 4). The graph indicates a notable influence concerning the cutting angle within the pale of the cutting operation.

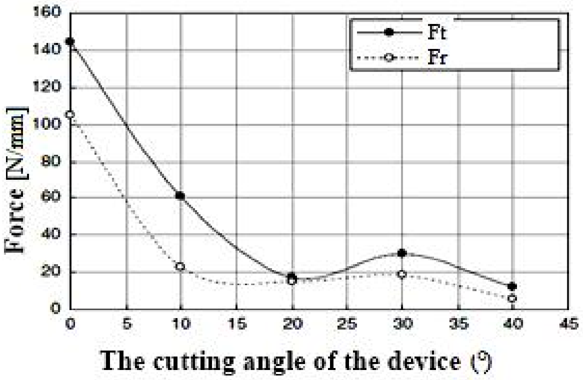


Figure 5: Variation graphs of the cutting resistance forces related to the cutting angle [7]

For low values of the cutting angle, are obtained high values for both of the forces, but there is a noticeable difference between the values of the two forces, fact that highlights the influence of friction and adhesion forces.

When cutting angle increases, the area of contact surface between the blade and the newly created surfaces is reduced, leading to lower values of the two forces. The minimum value of the two forces is obtained for a value of the cutting angle of 20°. For a cutting angle of 30°, is obtained a local maximum value, then when the values of the cutting angle increases, the values of the two forces are reduced again.

Numerous studies have highlighted the geometrical effect of the cutting edge on the forces generated during the cutting operation. It was examined the effect of sharpening the cutting edge angle (its value ranging between 20° ... 50°). McCarthy et al. [6] revealed that while cutting, the cutting force increases with the increasement of the angle of sharpening the cutting edge.

3. CONCLUSIONS

1. Cutting is performed to vegetable to give the final product specific characteristic shapes and sizes.
2. The process of grind cutting may be divided into two stages: a first stage, when under the action of the cutting edge occurs the compression and the elastic deformation of the material surface and its cellular tissue; the second stage, the force exceeds a critical value, when it reaches a maximum and the material will deform plastic, cellular tissue is destroyed and cause the release of cellular juice, also is destroyed the integrity of the material, the knife penetrating the mass of material.

3. After penetrating the material mass, the sides of the knife blade are pressing against the newly created surfaces, causing splitting action. Between the wedge surfaces and created surfaces are acting new friction forces that oppose the knife movement.
4. As the knife penetrates further into the mass of material, the generated surfaces are pressing the knife into the mass of material; the strain energy is partially transformed into elastic energy. The tops of the variation curve are indicating resistance to cutting cell walls.
5. Strength of cut resistance consists of the following components: power consumption for plastic deformation and elastic force that overcomes friction and adhesion forces, the force of disintegration consumed by the knife blade in the material structure.
6. When cutting angle increases, the surface area of contact between the blade and the newly created surfaces is reduced, leading to lower values of the two forces.

REFERENCES

[1] Atkins T., The Science and Engineering of Cutting – The Mechanics and Process of Separating, Scratching and Puncturing Biomaterials, Metals and Non-metals, Elsevier, 2009.
[2] Căsăndroiu T., Ivănescu D., Experimental research on texture homogeneity firmness of the pulp apples, INMATEH, vol. 27, nr. 1, p. 131-138, 2009.
[3] Everstine G. C., Rogers T.G., A theory of machining of fiber-reinforced materials, Journal Compos. Mater., vol. 5, p. 94–106, 1971.
[4] Koplev A., Cutting of CFRP with single edge tools, Int. Conf. Compos. Mater., vol. 3, p. 1597–1605, 1980.
[5] Koplev A, Lystrup A, Vorm T., The cutting process, chips and cutting forces in machining CFRP, Composites, vol. 14, p. 371–376, 1983.
[6] McCarthy C.T., Hussey M., Gilchrist M.D., On the sharpness of straight edge blades in cutting soft solids: Part I – indentation experiments, Elsevier, Engineering Fracture Mechanics 74, p. 2205–2224, 2007.
[7] Mkaddem A., Demirci I., Mansori M., A micro–macro combined approach using FEM for modelling of machining of FRP composites: Cutting forces analysis, Composites Science and Technology 68, Elsevier, p. 3123–3127, 2008.
[8] Pitt RE., Models for the rheology and statistical strength of uniformly stressed vegetative tissue, Trans. ASAE, 25:1776-1784, 1982.
[9] Pitt RE., Chen HL., Time dependent aspects of the strength and rheology of vegetative tissue, Trans. ASAE, 26:1275-1280, 1983.
[10] Thiel B. L., Donald A. M., In situ Mechanical Testing of Fully Hydrated Carrots (Daucus carota) in the Environmental SEM, Annals of Botany, vol. 82, p. 727 -733, 1998.
[11] Verlinden B.E., De Barsy T., De Baerdemaeker J., Deltour R., Modeling the mechanical and histological properties of carrot tissue during cooking in relation to texture and cell wall changes, Journal of Texture Studies 27, p. 15 – 28, 1996.
[12] Vincent J. F., Fracture properties in plants, Advances in Botanical Research, vol. 17, p. 235 – 287, 1990.
[13] Zdunek A., Umeda M., Extension and fracture of cell walls after parenchyma tissue deformation Biosyst. Eng., 93 (3), pp. 269–278, 2006.