CHAPTER «AGRICULTURAL SCIENCES»

STUDY OF MECHANICAL-RHEOLOGICAL PARAMETERS OF FEED GRAIN DURING TO THE IMPACT-CUTTING LOADING

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DOI: https://doi.org/10.30525/978-9934-26-195-4-15

Abstract. The research is based on the tasks of applied research on the topic: «Development of a complex of energy-efficient and resource-saving equipment and promising technologies for feeding farm animals of the AIC of Ukraine», state registration number 0121U108589. The authors' research is aimed at solving current problems of technological renewal and development of the agro-industrial complex of Ukraine. Rationalisation of energy use necessitates the substantiation of the energy-saving variant by implementing energy-efficient machines and technologies in the system of feed preparation and feeding animals. Grinding largely determines the quality of compound feed, its digestibility by animals and birds, and has a significant impact on the growth of animal productivity, the profitability of the enterprise, the rhythm of work and production costs. Therefore, reducing the energy intensity of the process is an urgent task. In the laboratory of the theory of mechanisms and machines of the department of general technical disciplines and labor protection of Vinnitsa National Agrarian University, a vibratory disk crusher was designed to increase the level of technical support for the livestock industry. The crusher uses a more efficient method of grinding feed grain – a combination of impact and cutting, in contrast to a hammer mill that grinds with a free impact of hammers. Further improvement of the energy efficiency of grain grinding

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in a vibratory crusher requires theoretical studies of the process dynamics and determination of the minimum amount of energy required to break the grain. An effective and modern method for studying complex objects is system analysis, which makes it possible to modernize existing and design new machines without a large number of expensive physical experiments. The implementation of effective energy saving measures requires a deep theoretical study of the interaction of the material with the impact element of the crusher. Modelling for the grinding operation, it is necessary to consider structural-mechanical properties of the product, its ability to deform in different modes of interaction with the executive body of the technological machine. The total mechanical work expended on the destruction of the material and and energy intensity of the feed preparation process depends on this deformation. The aim of the research is to developing and analysing the mechanical-rheological model of the material, assess the process of relative deformation of maize grain during combined grinding by impact-cutting and determining the overall mechanical work for the destruction. The object of the research are the structural-mechanical properties of a maize grain, energy intensity of the process of destruction of an individual grain under conditions of impact-cutting action. The subject of the research is the regularities of the process of deforming a grain under the action of external load of the cutting edge of the crusher's impactor. The paper defines the values of absolute deformation and mechanical work performed during the destruction of corn grain under the action of an applied shock-cutting load. These characteristics are presented in analytical and graphic form. The results of these studies make it possible to establish the boundary values of the plastic and elastic absolute deformations occurring in the material. This is a necessary condition for further theoretical substantiation of the law of energy-saving grinding.

1. Introduction

Scientists point outs that [1], feed preparation constitutes 45-50 percent of the cost of prepared livestock products. In this case, the estimated energy costs for technological operations are distributed in the following way: transportation – 10…20%,, dosing – 5…8%, grinding (including grain material) – up to 45… 65% of total costs, that is approximately 33% of the cost of finished products [1; 2].

In opinions of many scientists, a significant condition for the organization of complete feeding for animals and poultry is the efficient use of grain feed and their rational preparation for feeding. The share of concentrated feeds in the total feed balance is 29...32%. Among cereals, maize grain has the highest nutritional value. It contains lots of carbohydrates, mainly starch (approximately 70%), fat (up to 6% or more), the amount of protein (9–12%). Nutritional value of 1 kg of grain – 1,33 fodder units. and 67–73 g of digestible protein. The efficiency of using grain without prior preparation is reduced by 10...20% [3; 4; 5; 6].

The most common ways of using grain in feeding animals is to introduce it into various feed mixtures and compound feeds, crushed or in the form of flattened, extruded, micronized and so on. One of the main ways of preparing feeds for feeding animals is grinding. Grinding is the main way of preparing grains for feeding animals, which allows increasing the digestibility of nutrients by 15–30% [4; 6].

Ibatullin I.I. and Zhukorskyi O.M. [6] believe that the degree of grinding influences the amount and enzymatic activity of digestive juices, the rate of passage of food through different parts of the digestive tract and, thus, the digestibility of nutrients and the productivity of animals. Consequently, the researches are aimed at intensifying the process of grinding the material for further use in the feed preparation system under the condition of reducing energy consumption and providing the required quality of the original product, are relevant and have practical value.

At present, on livestock farms and mixed feed mills for grain grinding large-scale acquisition of hammer crushers. In these process machines, material destruction occurs due to sequentially flowing stages: application of the distributed load with the flat face of a hinged and suspended hammer, occurrence in the body of various deformations and tension growth, achievement of boundary values of stresses and deformations, breaking the bonds between atoms and molecules.

Most fracturing in the crushing process is brittle and plastic. The brittle fracture is characterized by a slight deformation of the material and there are no permanent deformations after fracture.

The applied energy is used to overcome the forces of mutual clutch of the body particles, that is, to form a new surface. When plastic materials are destroyed, energy is wasted both on breaking structural bonds and on significant ones plastic deformations. The energy used for deformation is turned into heat. The strength of a material and its maximum deformation are determined by the structural and mechanical characteristics of the grain and depends on the variety, size, density, moisture content, temperature, etc.

Thus, if the moisture content is increased, the brittle and brittle strength decreases as the plasticity increases and the absolute deformation that grains can perceive before the destruction begins.

Grinding fragile materials requires significantly less energy than plastic. Since, as already noted, the fragility and plasticity of certain materials are determined by their physical condition, from an energy point of view, it is advisable to grind the material in a fragile state. Experience has shown that fodder production is primarily based on fodder with a moisture content greater exceeding the basic conditions. This is due to material aspects (the market value of raw grains is much lower), and the production capacity of a particular enterprise. As noted, there is a low efficiency in grain grinding above the basic condition the crushing method by impact, which is caused by the increased plasticity of the material and the increase in the value of the limit deformation, that grain can perceive as destroying. The late removal of the finished material from the grinding area due to It is present on the screen, resulting in reduced crusher throughput. In order to reduce costs, the introduction of grain grinding machines proposed by Sergey N.S., Abramov A.A., Nanka O.V. [1; 29; 30] the operating principle is based on the combination of cutting and scaling techniques.

The advantage of this combination is local over-voltage of surface microvolumes at load application sites. During cutting, the blade of the knife is inserted into the product and at the contact surface a specific pressure sufficient to destroy the body. However, the problem of creating stagnant areas in the working space of crushers due to the presence of wet material remains unresolved.

To improve the technical level of the livestock industry in the laboratory Theory of mechanisms and machines of the Department of General Technical Disciplines and Occupational Safety Vinnitsa National Agrarian University designed vibration disk crusher, which is characterised by the use of a more efficient method for grinding a substandard (fodder) grain combicorm – impact combination, compared to existing hammer crushers, based on the use of free impact on the material of hinged plates – hammers.

Also by ensuring that the working part of the machine and the working chamber fluctuate together the separation surface allows for the timely release of the product from the grinding area, which reduces excessive circulation of the food and air layer the final product is removed from the zone grinding, and as a consequence, creates the potential for reducing the specific energy costs of such processing.

This combination of grinding techniques (impact and cutting) makes it possible to treat a substandard raw material with a high moisture content and with a reduction in the energy consumption of a given technological operation, as confirmed by the results of experimental studies. However, despite the overall reduction in energy intensity, further energy conservation measures requires a more in-depth theoretical study of the interaction of the material with the impactor of the process machine.

2. Analysis of recent research and publications

The creation of modern high-performance technological systems, including, for example, the system «crusher – grain material» is based on the mandatory justification of certain applied engineering and design solutions. One of the stages of such design is to determine the patterns of the movement of the machine and define the optimal parameters of the technological process on this basis. An essential aspect is the substantiation and choice of the calculation model, which adequately reflects the real movement of the system «machine – raw materials».

The initial data for modelling the processes of mechanical grinding are information on the structural-mechanical properties of the processable object [7; 8], the kinetics of deformation [9], the critical values of the internal force factors at which the destruction of the structure occurs [10; 11]. The process and the nature of the destruction of the grain result from the modes of its contact interaction with the executive body of the crusher, including the configuration and geometric parameters of the impactors. So, to obtain a comprehensive mathematical model that would cover the specifics of the contact interaction of the processable object with the executive bodies of the machine is a necessary condition for the development and analysis of the mechanical-rheological model of maize grain.

In the process of grinding under the action of forces applied to the workpiece, which exceed the temporary resistance or the limit of its strength, elastic and plastic deformations are formed, resulting in microcracks, which divide the material into particles. When external influences act within the elasticity, cracks due to molecular relationships can be closed, ie the destruction of the body does not occur. When external forces exceed the elastic limit, there is a grinding process, which is closely related to energy consumption time of their deformation, interaction between themselves and the executive body of the machine. There are a number of hypotheses for determining the energy consumption for grinding [22; 23; 24].

According to Rittinger's surface hypothesis, the work spent on grinding is proportional to the size of the newly formed surface of the crushed material, which takes into account the energy required to separate the crushed material on one plane and is expressed by the following dependence:

$$A_s = K_{pr} \cdot S, \qquad (1)$$

K_{pr} – is the coefficient of proportionality J/m^2; S – the value of the newly formed surface m^2.

The total energy A∑ (J) for grinding a certain size D_c depending on the size d of the source material is:

$$A\sum = 3A_s\left(\frac{D_c}{d} - 1\right) = 3A(i-1) \qquad (2)$$

$i = \frac{D}{d}$ – the degree of grinding of the material.

From the given dependence it is seen that the work spent on the specified process is proportional to the degree of grinding of the processed material or the size of the newly formed surface.

According to the theory of V.N. Kirpichev and later – F. Kika, The energy consumption for this process is proportional to the volume of the body and, as a consequence, to the product of the work A_V ,. shredding of two bodies with volumes V:

$$A_V = K_V \cdot V = K_V \cdot D_c^3, \qquad (3)$$

K_V – empirical coefficient of proportionality, J/m^3; V – volume of cubic body with rib D.

The disadvantage of the Rittinger and Kirpichev-Kik conjectures is the absence of numerical values of the specific coefficients, which makes implementation difficult.

There is the F. Bond Act, that the total energy must contain deformation and the formation of new surfaces. Bond's law states that energy is first distributed by mass and in sum proportional D^3 and from the moment the crack is formed on the surface is proportional D^2.

Then full power:

$$A = K_e \cdot \sqrt{V \cdot S} = K_e \cdot D^{2,5}, \quad (4)$$

where D – minimum size of material; K_e – experimental coefficient.

So according to the volumetric theory, the work carried out by shredding is proportional to the volume of bodies, and the force applied is proportional to the surfaces of these objects.

The founder of physico-chemical mechanics P.O. Rebinder believed that the conjecture, the closest to the truth is in the middle of the assumptions of Rittinger and Brick Kik, The amount of work spent on shredding is the sum of two parts:

$$A = \sigma\Delta F + k\Delta V, \quad (5)$$

where σ – is the specific energy assigned to the unit of the surface of the body; F – is the surface of the body formed by the break-up; k – is the specific activity of elastic and plastic deformations assigned to the unit of volume of the solid body; ΔV – is the volume of the deformed body.

Thus, the desired operation of this process is proportional to the newly formed surface, and the amount of material to be ground. It is obvious that in the initial stage of large grinding the main work is spent on deformation of the body, New surfaces are few in number and the second component has little numerical value. The energy consumption during grinding increases as the size of the particles decreases. Therefore, in order to avoid unproductive costs, In order to organize the process, the expected size of the feedstock particles should be known in advance. In order to reduce the energy consumed, it is advisable to remove sufficiently shredded particles from the grinding zone periodically.

The heterogeneity of the mass of the technological environment, the influence of its individual components, the interaction between the surfaces of the vibrating container, deformation and destruction of loading particles in a collision and a number of other external and internal factors make it difficult to theoretically study the dynamics of vibrating process machine. At the same time note the mechanical methods of analysis, which describe the interaction of the working bodies of the machine with the technological environment as a mechanical object; rheological, which allow to reveal the internal processes in the environment, operating on such properties as elasticity, viscosity, ductility and to some extent the strength of the components of the load mass. Therefore, we can distinguish respectively mechanical and rheological models of the technological environment.

Depending on the mechanism of creation, it is worth noting the mathematical models described using the methods of physical kinetics and similarity theory, based on the processing of experimental data; in the form of an algebraic model, whose constants are determined from the experiment; in the form of theoretical and probabilistic models; in the form of a phenomenological or rheological model based on information about the properties and behavior of the technological environment obtained as a result of experimental research.

However, the main classification feature of the types of mathematical models of the technological environment is the object of study, which served in the works of various scientists and the material point, and flat layers of the medium, and loading as a continuous medium, and a set of particles with a certain set of connections between them, etc. [13–18].

A thorough description of the principles of construction of rheological models and examples of creating with their characteristic models of the technological environment of vibrating machines are given in [1; 5–13]. In Figure 1 presents the simplest schemes of these models, containing components, each of which has some rheological equations.

For the elastic component, the characteristic parameter is the modulus of elasticity G, for the viscous component – the viscosity coefficient η, for the plastic component – the yield strength $\sigma_т$. In order to describe the process of compaction of the medium, it is advisable to use a complex plastic model, which consists of several plastic bodies connected in series with the gap Δ, which having different yield strengths. For a given body, with increasing deformation, an increasing number of particles are involved in the movement, which corresponds to an increase in yield strength [15]. A similar effect is also described by the wedge model, for which the increase in yield strength is carried out according to the linear law. The elastic-plastic body changes its properties first according to law Hooke's, and when it reaches the yield strength, it begins to deform plastically. For an elastic-plastic strength body

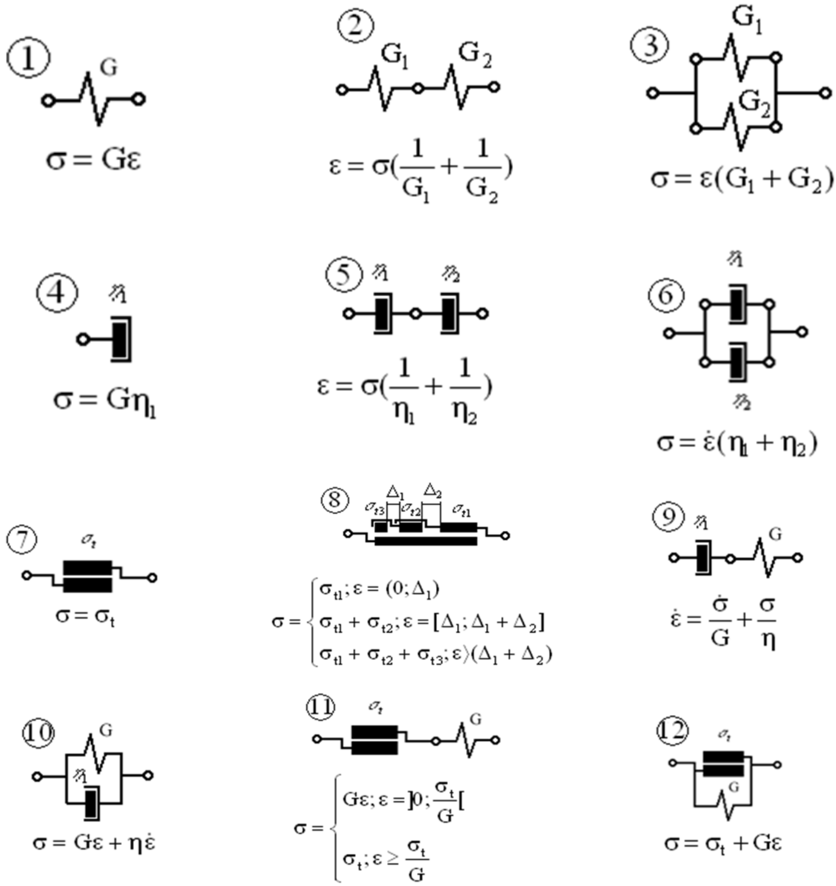


Figure 1. Analysis of the characteristics of rheological models:
1 – simple elastic body; 2 – consistent connection of elastic bodies; 3 – parallel connection of elastic bodies; 4 – simple viscous body; 5 – consistent connection of viscous bodys; 6 – parallel connection of viscous bodys; 7 – simple plastic body; 8 – plastic strength body; 9 – elastic-viscous liquid; 10 – elastic-viscous solid body; 11, 12 – elastic-plastic body

with increasing strain, the stress increases linearly, then remains equal to the yield strength $\sigma_{т2}$ of the first plastic element and after leveling the gap Δ_2, increases again to the yield strength $\sigma_т$. After unloading, the stresses in the body are not completely removed: there are internal stresses equal to the sum of yield stresses [16].

For an elastic-plastic body with wedge elements after unloading, the stresses are removed according to the linear law, and the residual deformation is equal to the plastic one.

With the deformation of the elastic-viscous body, its deformation will approach the nominal σ/g asymptotically and will reach it only after infinite time. This phenomenon of delayed deformation of elastic-viscous bodies is quite significant in processes where there are modes with periodic loads. Also, the intensity of the loading and unloading processes significantly depends on the value of η/G, which is called the delay time. When the mentioned ratio increases, the deformation processes are slower, the delays increase. The combination of the simplest models of rheological bodies makes it possible to reproduce with any degree of reliability almost any properties of the environment, including in the evaluation of multiphase systems.

3. Purpose and objectives

The aim of the research is to developing and analysing the mechanical-rheological model of the material, assess the process of relative deformation of maize grain during combined grinding by impact-cutting and determining the overall mechanical work for the destruction.

The research is based on classical theory of mechanical oscillations Theory of vibrational grinding, mechanics of dispersed media, mechanics of a solid body, III theory of strength. The physico-mechanical properties of cereal crops include resistance due to mechanical stresses deformation and its nature during destruction, degree of grinding and preserve the raw material's basic properties during its processing. Humidity and hygroscopy are the main physical properties of bulk systems, in particular grain-based raw materials (i.e. body's ability to sorb vapour water), bulk density (i.e. the mass of a unit of volume occupying the material at a free mound over a certain surface area), apart, etc.

The value of the powder depends on the method by which the particles are laid, their shape, their size (table 1) and the influence of external factors.

Table 1

Geometric characteristics of the main types of grain for feed production [29]

Crops	Length, mm	Width, mm	Thickness, mm	Volume, V mm·10^{-3}
Wheat	4.1-8.5	1.6.-4.0	1.5-3.8	19-42
Rye	5.0-10.0	1.4-3.7	1.2-3.6	10-30
Barley	7.0-14.6	2.0-5.0	1.4-4.6	20-40
Corn	5.5-13.7	5.0-11.6	2.5-8.1	140-260

Thus, under the influence of vibration, this value for the same material can vary from 1.1 to 3 times or more. The change in the structure of the bulk layer under compression load is characterised by the compaction coefficient $k_c=q_b0/q_b$, where q_h0, q_n – the bulk density of the material is initial and post-pressing respectively.

In previous studies [30], the author found that the relative compression of the grain is proportional to the crushing force, and the limit of proportionality, in turn, changes depending on the moisture content of the grain (Table 2).

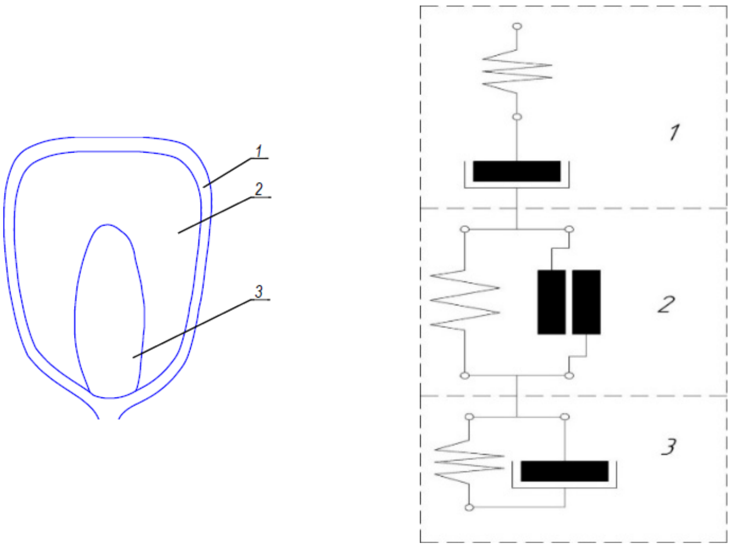
As can be seen from the table, corn has the highest strength. For it, the ultimate breaking force is from 150 to 350 N. The lowest indicator for soft varieties of wheat and rye is 68-88 N and 60-90 N, respectively. Therefore, as the object of technological action (material for research), we use corn grain.

Having derived the equations of elastic and plastic deformation of grain, rheological methods of researching dispersed systems, empirical constants and reference data on the structure, physical properties, chemical composition, absolute mass, biological features of anatomical parts of a

Table 2

Ultimate fracture strength of cereal grains [30]

Humidity, %	Strength Before Breaking, *N*			
	Wheat	Rye	Barley	Corn
13-14	146-166	120-155	197-200	330-350
15-16	138-145	110-118	184-195	300-328
17-18	118-136	103-109	175-182	255-297
19-20	92-116	92-101	162-174	205-250
21-22	68-88	60-90	151-160	150-204



a **b**

Figure 2. Maize grain: a) anatomical structure; b) rheological model; 1 – hull; 2 – endosperm; 3 – germ

maize grain: germ, endosperm, outer and inner pericarps have been used (Figure 2a).

The solution of analytical expressions and graphical interpretation of the obtained results have been performed using specialised software MS Excel 2020, MathCad 15.

The object of the research are the structural-mechanical properties of a maize grain, energy intensity of the process of destruction of an individual grain under conditions of impact-cutting action. The subject of the research is the regularities of the process of deforming a grain under the action of external load of the cutting edge of the crusher's impactor.

4. Results and discussion

Maize grain is the only entire organic compound that is sharply heterogeneous in its structure, physical properties, chemical composition, absolute mass, biological purpose of the anatomical parts.

Thus, this processable object can be characterised as an elastic-viscous-plastic, colloidal, capillary-porous body, with a protein framework, starch filler and cellulose hull, that makes it difficult to carry out experimental assessment of mechanical-technological properties of the processable object. In order to formalize the objective of researching the process of deforming a grain, we have proposed a simplified six-link model of a maize grain as the most acceptable rheological model for a wide range of actions (Figure 2b).

The proposed model is a sequential connection of the model of the Maxwell ideal body (describes the elastic hull of the grain containing bound moisture), the body is a parallel connection of Hooke's model of the ideal-elastic body with Saint-Venant's model of the ideal plastic body (describes the behaviour of floury endosperm containing an elastic-plastic starch filler) and the model of the Kelvin body (describes the behaviour of an elastic germ containing molecular moisture).

For a mathematical description of the behaviour of the proposed rheological model of the grain (Figure 2b) under the influence of the applied force F let us consider separately each of the three bodies listed above: M, HStV and K. The Maxwell body (M) (Figure 3) is a sequential connection of Hooke's ideal-elastic body (H) with Newtonian ideal-viscous fluid (N).

As a wide-ranging uniform pressure in each material, regardless of its rheological properties, causes elastic deformation, accompanied by tangential stresses, in each of these three bodies (M, HStV and K), under the influence of the applied force, the same tangential stresses τ will occur [12; 13].

On the basis of the above mentioned, under the action of the applied force F, there is a tangential stress τ, which for each element M-body is the same:

$$\tau_1 = \tau_2 = \tau \,, \tag{6}$$

and the deformation γ, that occurs in M-body, is equal to the sum of the deformations of each of its elements:

$$\gamma = \gamma_1 + \gamma_2 \,. \tag{7}$$

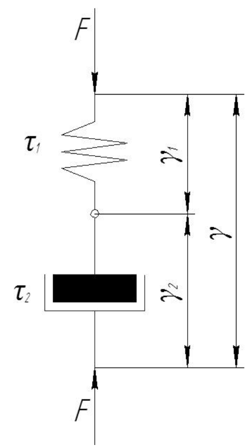


Figure 3. Rheological model of the a maize grain hull

The tangential stress τ, that takes place in the H-body, can be determined according to Hooke's law by the formula:

$$\tau = \mu \cdot \gamma_1 , \tag{8}$$

where the deformation, that occurs in the H-body, can be found:

$$\gamma_1 = \frac{\tau}{\mu} , \tag{9}$$

where: μ is the shear modulus.

Differentiating equation (9), we shall obtain the equation of the strain rate that occurs in H-body:

$$\frac{d\gamma_1}{dt} = \frac{1}{\mu} \cdot \frac{d\tau}{dt} . \tag{10}$$

The tangential stress τ, which occurs in N – body, can be determined by the formula:

$$\tau = \eta \cdot \frac{d\gamma_2}{dt} , \tag{11}$$

so we obtain the equation of the rate of deformation, that is taking place in the body:

$$\frac{d\gamma_2}{dt} = \frac{\tau}{\eta} , \tag{12}$$

where η is the coefficient of viscosity.

Differentiating equation (7), we shall obtain the equation of the strain rate that occurs in M-body:

$$\frac{d\gamma}{dt} = \frac{d\gamma_1}{dt} + \frac{d\gamma_2}{dt} . \tag{13}$$

Substituting equations (10) and (12) into equation (13), we shall finally obtain the equation of the strain rate that occurs in M-body:

$$\frac{d\gamma}{dt} = \frac{1}{\mu} \cdot \frac{d\tau}{dt} + \frac{\tau}{\eta} . \tag{14}$$

HStV body (Figure 4) is a parallel connection of the perfectly elastic Hooke's body (H) with Saint-Venant's ideal-plastic body (StV).

When the elements are connected in parallel, the total voltage on the model is equal to the sum of the voltages on each element, the tangential voltage τ that occurs in HStV body, can be defined in the following way:

$$\tau = \tau_1 + \tau_2 . \tag{15}$$

The tangential stress τ_1, that occurs in H-body:

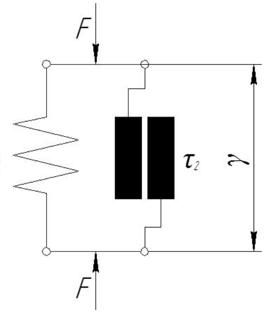


Figure 4. Rheological model of maize grain endosperm

$$\tau_1 = \mu \cdot \gamma_1, \quad (16)$$

where: μ is the shear modulus, γ_1 is the deformation, that occurs in H body.

The tangential stress τ_2, which take place in HStV body is:

$$\tau_2 = \tau_T, \quad (17)$$

τ_T is the shear yield strength.

Substituting equations (16) and (17) into equation (15) we obtain:

$$\tau = \mu \cdot \gamma_1 + \tau_T, \quad (18)$$

In the case of parallel connection of elements the total deformation of model γ is equal to the deformation of each element:

$$\gamma_1 = \gamma_2 = \gamma, \quad (19)$$

then the equation of deformation, that occurs in HStV body, can be expressed by the equation (18):

$$\gamma = \frac{\tau - \tau_T}{\mu}. \quad (20)$$

Differentiating equation (20), we obtain the equation of the strain rate, that occurs in HStV body:

$$\frac{d\gamma}{dt} = \frac{1}{\mu} \cdot \left(\frac{d\tau}{dt} - \frac{d\tau_T}{dt} \right). \quad (21)$$

As the shear yield strength is constant value τ_T = const, then equation (21) will take the following form:

$$\frac{d\gamma}{dt} = \frac{1}{\mu} \cdot \frac{d\tau}{dt}. \quad (22)$$

The Kelvin-Voigt body (K) (Figure 5) is a parallel connection of Hooke's ideal-elastic body (H) with Newtonian ideal-viscous fluid (N).

The tangential stress τ, that appears in K-body, can be found using the formula:

$$\tau = \tau_1 + \tau_2. \quad (23)$$

According to Hooke's law, the tangential stress τ_1 arises in H-body:

$$\tau_1 = \mu \cdot \gamma_1, \quad (24)$$

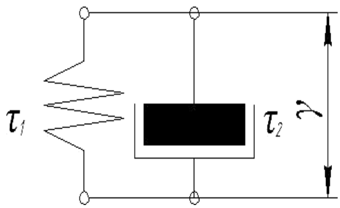


Figure 5. Rheological model of maize grain germ

where: μ is the shear modulus, γ_1 is the deformation, which takes place in H-body.

The tangential stress τ_2, that occurs in N – body:

$$\tau_2 = \eta \cdot \frac{d\gamma_2}{dt}, \tag{25}$$

where: η is the shear viscosity coefficient.

Substituting equations (24) and (25) into equation (23), we shall obtain:

$$\tau = \mu \cdot \gamma_1 + \eta \cdot \frac{d\gamma_2}{dt}. \tag{26}$$

Differentiating equation (26), we shall obtain:

$$\frac{d\tau}{dt} = \mu \cdot \frac{d\gamma_1}{dt} + \eta \cdot \frac{d^2\gamma_2}{dt^2}, \tag{27}$$

then:

$$\frac{\eta}{\mu} \cdot \frac{d^2\gamma_2}{dt^2} + \frac{d\gamma_1}{dt} = \frac{1}{\mu} \cdot \frac{d\tau}{dt}. \tag{28}$$

Absolute deformation of model γ:

$$\gamma_1 = \gamma_2 = \gamma. \tag{29}$$

After that the equation (28) will take the following form:

$$\frac{\eta}{\mu} \cdot \frac{d^2\gamma}{dt^2} + \frac{d\gamma}{dt} = \frac{1}{\mu} \cdot \frac{d\tau}{dt}. \tag{30}$$

So the equation of the strain rate, that occurs in K-body, can be obtained:

$$\frac{d\gamma}{dt} = \frac{1}{\mu} \cdot \frac{d\tau}{dt} - \frac{\eta}{\mu} \cdot \frac{d^2\gamma}{dt^2}, \tag{31}$$

or:

$$\frac{d\gamma}{dt} = \frac{1}{\mu} \cdot \left(\frac{d\tau}{dt} - \eta \cdot \frac{d^2\gamma}{dt^2} \right). \tag{32}$$

Subsequently, let us consider a series connection of M and HStV bodies, in which the deformations, which occur in them, are added:

$$\gamma = \gamma_1 + \gamma_2. \tag{33}$$

Differentiating equation (33), we shall obtain the equation of the strain rate that occurs in the M-HStV-body:

$$\frac{d\gamma}{dt} = \frac{d\gamma_1}{dt} + \frac{d\gamma_2}{dt}. \tag{34}$$

Substituting the equation of the strain rate, that occurs in the M-body (14), and the equation of the strain rate, that occurs in the HStV body (22) in equation (34), we shall finally obtain the equation of the strain rate, that occurs in the M-HStV-body:

$$\frac{d\gamma}{dt} = \frac{1}{\mu_1} \cdot \frac{d\tau}{dt} + \frac{\tau}{\eta} + \frac{1}{\mu_2} \cdot \frac{d\tau}{dt}, \tag{35}$$

or:

$$\frac{d\gamma}{dt} = \frac{1}{\mu_1} \cdot \frac{d\tau}{dt} + \frac{1}{\mu_2} \cdot \frac{d\tau}{dt} + \frac{\tau}{\eta}. \tag{36}$$

The series connection of M-HStV and K bodies enables building the proposed rheological model of grain (Figure 2b). Taking into consideration the above mentioned data, we shall find the deformation that occurs in this series connection:

$$\gamma = \gamma_1 + \gamma_2. \tag{37}$$

Differentiating equation (37), we shall obtain the equation of the strain rate that occurs in the M-HStV-K-body:

$$\frac{d\gamma}{dt} = \frac{d\gamma_1}{dt} + \frac{d\gamma_2}{dt}. \tag{38}$$

Substituting the equation of the strain rate, that occurs in the M-HStV-body (36), and equation (32) in equation (38), we shall finally obtain the equation of the strain rate that occurs in the M-HStV-K-body:

$$\frac{d\gamma}{dt} = \frac{1}{\mu_1} \cdot \frac{d\tau}{dt} + \frac{1}{\mu_2} \cdot \frac{d\tau}{dt} + \frac{\tau}{\eta_1} + \frac{1}{\mu_3} \cdot \left(\frac{d\tau}{dt} - \eta_2 \cdot \frac{d^2\gamma}{dt^2} \right), \tag{39}$$

then:

$$\frac{d\gamma}{dt} = \frac{1}{\mu_1} \cdot \frac{d\tau}{dt} + \frac{1}{\mu_2} \cdot \frac{d\tau}{dt} + \frac{\tau}{\eta_1} + \frac{1}{\mu_3} \cdot \frac{d\tau}{dt} - \frac{\eta_2}{\mu_3} \cdot \frac{d^2\gamma}{dt^2}, \tag{40}$$

or:

$$\frac{\eta_2}{\mu_3} \cdot \frac{d^2\gamma}{dt^2} + \frac{d\gamma}{dt} = \frac{1}{\mu_1} \cdot \frac{d\tau}{dt} + \frac{1}{\mu_2} \cdot \frac{d\tau}{dt} + \frac{1}{\mu_3} \cdot \frac{d\tau}{dt} + \frac{\tau}{\eta_1}. \tag{41}$$

As the proposed rheological model (Figure 2b) structurally consists of three complex bodies (M, HStV and K), but mathematically describes one body – grain, then the coefficients of elasticity and viscosity of these bodies can be considered as equal:

$$\mu_1 = \mu_2 = \mu_3 = \mu\,, \tag{42}$$

$$\eta_1 = \eta_2 = \eta\,. \tag{43}$$

So equation (41) will take the following form:

$$\frac{\eta}{\mu}\cdot\frac{d^2\gamma}{dt^2}+\frac{d\gamma}{dt}=\frac{1}{\mu}\cdot\frac{d\tau}{dt}+\frac{1}{\mu}\cdot\frac{d\tau}{dt}+\frac{1}{\mu}\cdot\frac{d\tau}{dt}+\frac{\tau}{\eta}\,, \tag{44}$$

Consequently:

$$\frac{\eta}{\mu}\cdot\frac{d^2\gamma}{dt^2}+\frac{d\gamma}{dt}=\frac{3}{\mu}\cdot\frac{d\tau}{dt}+\frac{\tau}{\eta}\,. \tag{45}$$

Dividing the left and right parts of equation (45) by $\frac{\eta}{\mu}$, we shall obtain:

$$\frac{d^2\gamma}{dt^2}+\frac{\mu}{\eta}\cdot\frac{d\gamma}{dt}=\frac{3}{\eta}\cdot\frac{d\tau}{dt}+\frac{\mu\cdot\tau}{\eta^2}\,. \tag{46}$$

The obtained expression is a second order differential equation. To solve it, we use the method of Reduction of order derivatives by means of a transition. To do this, we shall denote:

$$\frac{d\gamma}{dt}=z(t)\,, \tag{47}$$

$$\frac{d^2\gamma}{dt^2}=\frac{dz}{dt}\,. \tag{48}$$

Then equation (46) can be written as a first-order differential equation:

$$\frac{dz}{dt}+\frac{\mu}{\eta}\cdot z=\frac{3}{\eta}\cdot\frac{d\tau}{dt}+\frac{\mu\cdot\tau}{\eta^2}\,. \tag{49}$$

The solution of this differential equation will be the expression of the following form:

$$z=e^{-\int_0^t\frac{\mu}{\eta}dt}\left[\int_0^t\left(\frac{3}{\eta}\cdot\frac{d\tau}{dt}+\frac{\mu\cdot\tau}{\eta^2}\right)\cdot e^{\int_0^t\frac{\mu}{\eta}dt}dt+C_0\right]. \tag{50}$$

Thus, like at the beginning of the process of grain destruction by impact cutting it is in a relaxed state, arbitrary constant $C_0 = 0$:

$$z=e^{-\int_0^t\frac{\mu}{\eta}dt}\left[\int_0^t\left(\frac{3}{\eta}\cdot\frac{d\tau}{dt}+\frac{\mu\cdot\tau}{\eta^2}\right)\cdot e^{\int_0^t\frac{\mu}{\eta}dt}dt\right]. \tag{51}$$

The process of grain destruction of by impact cutting consists of three successive phases. The first phase is the contact of the grain with the blade, resulting in a compression stress, which is characterised by the magnitude of its deformation. The second phase occurs when the compressive stress reaches a certain limit caused by the strength of the grain, and is manifested in the formation of cracks in it. The third phase is the ultimate destruction of the coherent structure [14].

Since maize grain is an aggregate of individual bodies of inhomogeneous structure, some of which have a lower yield strength than others. If some force F is applied to the body, some parts of it are subjected only to elastic deformations, and others begin to flow, after a while they are gradually released from stress and it begins to distribute to more elastic parts of the grain, therefore, the stress in this part increases and deformation increases [15; 16].

After the inverse transition according to equations (47, 48) we shall obtain:

$$\frac{d\gamma}{dt} = e^{-\int_0^t \frac{\mu}{\eta} dt} \left[\int_0^t \left(\frac{3}{\eta} \cdot \frac{d\tau}{dt} + \frac{\mu \cdot \tau}{\eta^2} \right) \cdot e^{\int_0^t \frac{\mu}{\eta} dt} dt \right]. \tag{52}$$

Integrating equation (52), we shall finally obtain the equation for defining the value of deformation that occurs in M-HStV-K body:

$$\gamma = \left[\tau \left(\frac{e^{-\frac{2\mu \cdot t}{\eta}} - 1}{2\mu} - \frac{e^{-\frac{\mu \cdot t}{\eta}} - 1}{\mu} \right) \right]^{\frac{\mu \cdot t}{\eta}} \tag{53}$$

Since the structural and mechanical properties of the material are significantly affected by moisture content, in table 3. the values of rheological coefficients for maize grain are presented at a moisture content of 13% to 26% [17; 18].

Table 3

Values of rheological coefficients for maize grain [18]

Moisture content W, %	**13-14**	**16-17**	**19-20**	**22-23**	**25-26**
Shear modulus, μ (MPa)	8,61	5,07	3,05	2,43	2,25
Viscosity coefficient, η (MPa·s)	29,68	20,22	14,22	11,51	10,87
Strength limit, $\tau_{max.}$ (MPa)	2,9	1,75	1,035	0,875	0,825

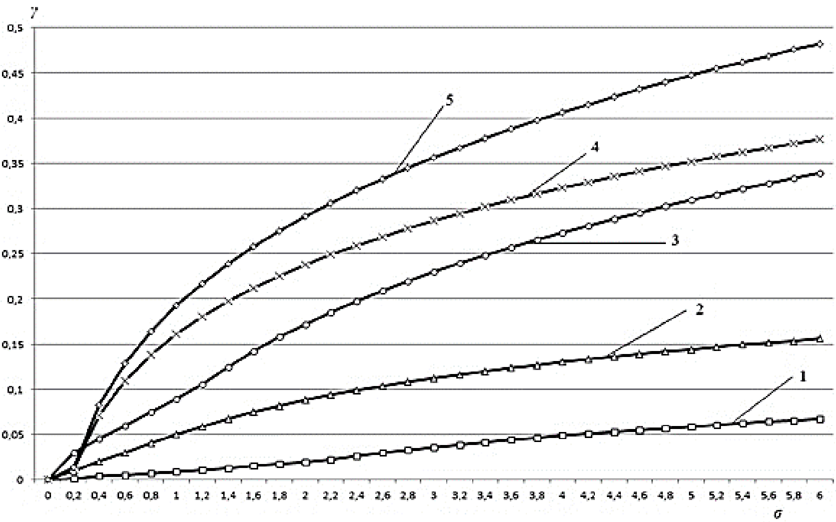


Figure 6. Dependence of the relative deformation of maize grain on normal stresses at moisture values: 1. W=13-14%; 2. W=16-17%; 3. W=19-20%; 4. W=22-23%; 5. W=25-26%

This values which have been obtained by other scientists and used by us as empirical constants for solving equation (53) and graphical interpretation of the laws of deformation of feed grain (Figure 6).

The absolute deformation that occurs in the grain under the action of the applied load can be represented as:

$$\Delta h = \gamma \cdot b \,, \tag{54}$$

where: γ – is the relative deformation of the material; b – grain thickness, m.

Theoretically, the work of destruction of one grain under shock-cutting load can be found by the dependence:

$$A^T = F \cdot \Delta h = F \cdot \gamma \cdot b \,, \tag{55}$$

where: F – is the load applied to the grain, N.

Since, the normal stresses arising in the grain under the action of the applied load can be represented as:

$$\sigma = \frac{F}{A}, \tag{56}$$

where: A – is the cross-sectional area of the grain, m^2;
Then:

$$F = \sigma \cdot A. \quad (57)$$

Given that according to the III theory of strength under uniaxial loading:

$$\tau_{max} \approx \frac{\sigma}{2}, \quad (58)$$

$$\sigma = 2\tau_{max}. \quad (59)$$

Substituting expressions (54) and (59) in (55) we obtain:

$$A^T = 2\tau_{max} \cdot A \cdot \left[\tau_{max} \cdot \left(\frac{e^{-\frac{2\mu \cdot t}{\eta}} - 1}{2\mu} - \frac{e^{-\frac{\mu \cdot t}{\eta}} - 1}{\mu} \right) \right]^{\frac{\mu \cdot t}{\eta}} \cdot b. \quad (60)$$

Analytical and graphical interpretation of equation (60), which characterizing the theoretical work of destruction of corn grain by the impact element of the vibrating disc crusher, carried out in a mathematical environment MathCad 15 (Figure 7).

A database was adopted, which included values: rheological coefficients at different moisture content, average geometric characteristics of the grain [14] and the range of tangential stresses τ = 0…6 MPa.

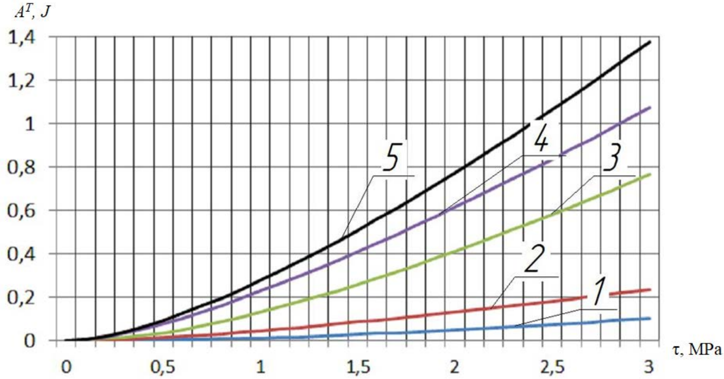


Figure 7. Dependence of theoretical work on the destruction of corn grain on normal stresses at moisture content: 1. W=13-14%; 2. W=16-17%; 3.W=19-20%; 4. W=22-23%; 5. W=25-26%

The energy used for grinding can be conditionally divided into the work used to overcome elastic and plastic deformation:

$$A_T = A_{ED} + A_{PD}, \qquad (61)$$

resulting in cracks in the material, and as a consequence of fracture.

Then, taking into account (5):

$$A_{ED} = e \cdot V; \quad A_{PD} = \beta \cdot V. \qquad (62)$$

Based on the theoretical break-up curves (Figure 7) and the relative grain deformation (Figure 6), find absolute plastic deformation, energy input to overcome elastic and plastic deformations and, respectively, the energy density coefficients e and β in the unit act of destruction (table 4), with grain volume V=250·10-9·m³.

Table 4

Parameters and coefficients of energy intensity of break-up of a single unit in total grain mass

Parameters	Relative humidity of material,%				
	13-14	16-17	19-20	22-23	25-26
A^T, J	$94 \cdot 10^{-3}$	$121 \cdot 10^{-3}$	$152{,}8 \cdot 10^{-3}$	$174 \cdot 10^{-3}$	$195{,}94 \cdot 10^{-3}$
A^T_{ED}, J	$12{,}19 \cdot 10^{-3}$	$36 \cdot 10^{-3}$	$47 \cdot 10^{-3}$	$65 \cdot 10^{-3}$	$82 \cdot 10^{-3}$
A^T_{PD}, J	$82{,}71 \cdot 10^{-3}$	$85 \cdot 10^{-3}$	$105{,}8 \cdot 10^{-3}$	$109 \cdot 10^{-3}$	$113 \cdot 10^{-3}$
e, $J \cdot m^{-3}$	$48{,}76 \cdot 10^3$	$144 \cdot 10^3$	$188 \cdot 10^3$	$260 \cdot 10^3$	$340 \cdot 10^3$
β, $J \cdot m^{-3}$	$330{,}84 \cdot 10^3$	$340 \cdot 10^3$	$423{,}2 \cdot 10^3$	$436 \cdot 10^3$	$452 \cdot 10^3$
γ	0,035	0,045	0,077	0,085	0,092
Δh, m	$0{,}22 \cdot 10^{-3}$	$0{,}283 \cdot 10^{-3}$	$0{,}484 \cdot 10^{-3}$	$0{,}535 \cdot 10^{-3}$	$0{,}579 \cdot 10^{-3}$

The obtained rheological parameters of corn grain and energy density coefficients e and β in a single act of destruction are the basis for further study of the dynamics of the process of grinding corn grain with a vibrating disc crusher, in particular the establishment of the relationship between the dispersion of the material and energy consumption to achieve it.

5. Conclusions

1. Therefore, based on the laws of solid mechanics and by applying rheological methods for the study of dispersed systems, the values of absolute deformation are presented and work carried out during the

destruction of corn grain under the action of the applied shock-cutting load in analytical and graphical form.

2. The rheological model of the fine medium is substantiated and the functional dependence of the deformation distribution on the force characteristics of the executive body and the moisture content of the material is determined. The nature of the curves (Figure 6) suggests that at the initial stage of application of the load to the grain, there are mainly elastic deformations, which are reflected in the form of straight sections on the graphs (linear dependences, which can be approximated by law Hooke's). For example, for grain with moisture content W=25-26% (curve № 5) in the range of tangential stresses τ = 0…0,19 MPa, there is a rapid linear increase in relative deformation to 0.08. With further increase (τ = 0,19…0,825 MPa) the shape of the deformation curve changes slightly and takes the form of a parabola branch, which may indicate the predominant plastic deformation that occurs in the grain, up to its destruction when τ = 0,825 MPa and relative deformation 0, 24.

3. At destruction of grain, with an indicator of moisture content 13-14% (Figure 7) theoretical work of fracturing includes work on overcoming elastic and plastic deformations and makes 0,09 J, at higher values of moisture content, for example 25-26% this show is 0.195 J. This difference in the work of destruction occurs due to the scattering of part of the kinetic energy of the impact disk in the grain due to its plastic deformation, and necessitates further research aimed at increasing the energy efficiency of the grinding process.

4. The obtained results of structural and mechanical characteristics and theoretical work of grain fracture (tabl. 4) allow to estimate the boundary values of plastic and elastic deformations, occurring in the material, which is the basis for further study of the dynamics of the process of grinding corn grain with a vibrating disc crusher, in particular the establishment of the relationship between the dispersion of the material and energy consumption to achieve it.

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