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Modeling the destruction of the grain shell of cereal crops

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Abstract. When processing grain cereals, hulling is an important part being the process of destruction of shell and separation of the fruit, from which cereals are prepared, which are a valuable food for people. As a result of theoretical research, a physicomathematical model of grain of cereal crops has been developed as a hulling object consisting of two separate structural elements (spherical shell and spherical kernel), each of which has its own geometric parameters and rheological properties. Mathematical dependences of the destructive stresses of the shell and kernel during static and dynamic interactions with working surfaces on their strength characteristics and geometric parameters are established. The obtained theoretical dependencies, together, represent a mathematical model describing the process of destruction of the grain shell of cereal crops under static and dynamic influences. It can be used to simulate sunflower seed shell hulling in vegetable oil production. The developed model provides quick and qualitative computational experiments with the use of computers and software, with the required set of given values of physical-mechanical and technological properties of the processed grain and structural and technological parameters of machines for destruction and separation of the shell. When using the appropriate software, it is possible to visualize the process of shell destruction with a full frame-by-frame picture of the distribution, magnitude, direction of loads and arising stresses. When using the appropriate software, it is possible to visualize the process of shell destruction with a full frame-by-frame picture of the distribution, magnitude, direction of loads and arising stresses. The possibility of solving this model using computer technology and modern software allows you to significantly reduce the labor intensity of natural experiments, while excluding random and systematic errors associated with the experimental equipment and the researcher.

1 Introduction

The hulling as the process of destructing the shell and separating the kernel (fruit) plays an important role in the technology of cereal grains and sunflower seeds processing [1-3].

The hulling quality is determined by the amount of maximum extraction of whole kernels in a single pass through the hulling machine [4]. The main factors affecting the quality are the anatomical structure and physical and mechanical properties of the processed grain, the method of hulling and design of the hulling machine. Experimental and theoretical material available in the literature shows a wide range of technologies based on the use of different methods and machines for hulling [3, 5-13].

When creating hulling machines, it is necessary to take into account the anatomical structure, physical and mechanical properties of the shell and kernel of the processed grains. Currently, this problem is solved experimentally individually for each crop and there are no theoretical provisions to justify the most effective method and design of the hulling machine.

The purpose of the study is to simulate the process of destructing the shell of cereal crops and the interaction with the working surfaces of hulling machines.

2 Materials and methods

Hulling is considered as a process of deformation of the shell beyond the elastic limit state and its destruction with separation from the kernel with the maximum preservation of the integrity of the latter. Before modeling the process of destruction and separation of the shell from the kernel, it makes sense to consider the physical and mathematical model of the grain, consisting of two elements - the shell and the kernel. Moreover, the shell is an object with different mechanical properties from the kernel, a separate object spatially separated from it by an air layer. The geometrical dimensions that characterize the shell as a hulling object are the diameter of the sphere D_s, shell thickness δ, air gap thickness δ', surface area S_s, volume V_s. The geometric parameters of the spherical body (kernel) are: ball diameter D_k, surface area S_k, volume V_k.

For mathematical recording of the equations establishing the relationship between these parameters, let's connect a spherical structural body modeling the hulling object with a moving coordinate system. And the

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coordinate system is chosen so that the origin of the coordinate system lies in the center of the spherical body. Since in this case we consider the model of a whole unshelled grain with undamaged structure, it is reasonable to express some parameters through those that can be determined experimentally.

Mathematical equations establishing the relationship between the listed geometrical parameters:

$$S_s = \pi D_s^2 ; S_k = \pi D_k^2 , \quad (1)$$

$$V_k = \frac{\pi D_k^3}{6} ; V_s = \frac{\pi}{6} \left[D_s^3 - \left(D_s - 2\delta \right)^3 \right], \quad (2)$$

$$D_s = 2 R_s ; D_k = 2 R_k . \quad (3)$$

The surface bounding the simulated body will be described by the following expression:

$$X^2 + Y^2 + Z^2 = R^2 . \quad (4)$$

In addition to geometric parameters, structural elements have physical and mechanical properties such as mass, density, humidity, which determine the physical state of the hulling object. Here it should be noted that the moisture content of the hulling object and mainly the difference in the moisture content of the W_k and seedcoat W_s have a significant impact on the process of hulling a single grain and on the indicators of technological efficiency of the working process in the flow.

From the point of view of fracture mechanics, a spherical shell is a solid elastic deformable body with certain strength characteristics. In addition, the shell has a number of properties, among which we will highlight its cleavability, fractibility under static and dynamic (shock) influences, which directly depend on the strength characteristics. The ball-shaped body (kernel) is an elastic and plastic body. Here, too, there are a number of properties reflecting crushability, destructibility, which are closely related to the moisture content of the kernel. Grain of cereal crops as a subject of hulling has a number of strength properties, which characterize the rigidity of structural elements under external force action. The most important ones, in our opinion, are the elastic modules of the shell E_s and kernel E_k, shell Poisson's coefficients μ_s and kernel μ_k.

We note that these characteristics depend on the physical state of the hulling subject and mainly on the moisture content. The listed properties determine the values of the limiting forces leading to the destruction of the shell, with the maximum preservation of the original geometrical parameters of the kernel.

The research used general scientific methods of mathematics, physics, theory of elasticity, theory of shells, physical and mathematical modeling, as well as private and specific methods of research cereal grains and technological processes of their processing [3,14-19].

3 Results and discussion

Based on the above materials, the model of the subject of hulling (grains) is presented in the following form (fig. 1).

The presented model of the subject is the basis for modeling the process of destruction of the grain shell of cereal crops. The presented model is universal, which allows one to describe the geometry and condition of almost all cereal seeds with different anatomical structure and physical and mechanical properties. The destruction of the shell of grain in the hulling machine is a consequence of their interaction with the working surfaces, which have certain mechanical characteristics. Therefore, in this case it makes sense to consider simplified models of a single-grain shell fracture during interaction with the working surface. Let us consider the process of interaction of the grain with the working surface on the assumption that it behaves as an elastic shell of the finite thickness. The stiffness of the working surface is an order of magnitude higher than the stiffness of the shell, so only its deformation occurs. The elastic material properties of the working surface are taken into account in the calculations through the modulus of elasticity (Ep) and Poisson's ratio (μp).

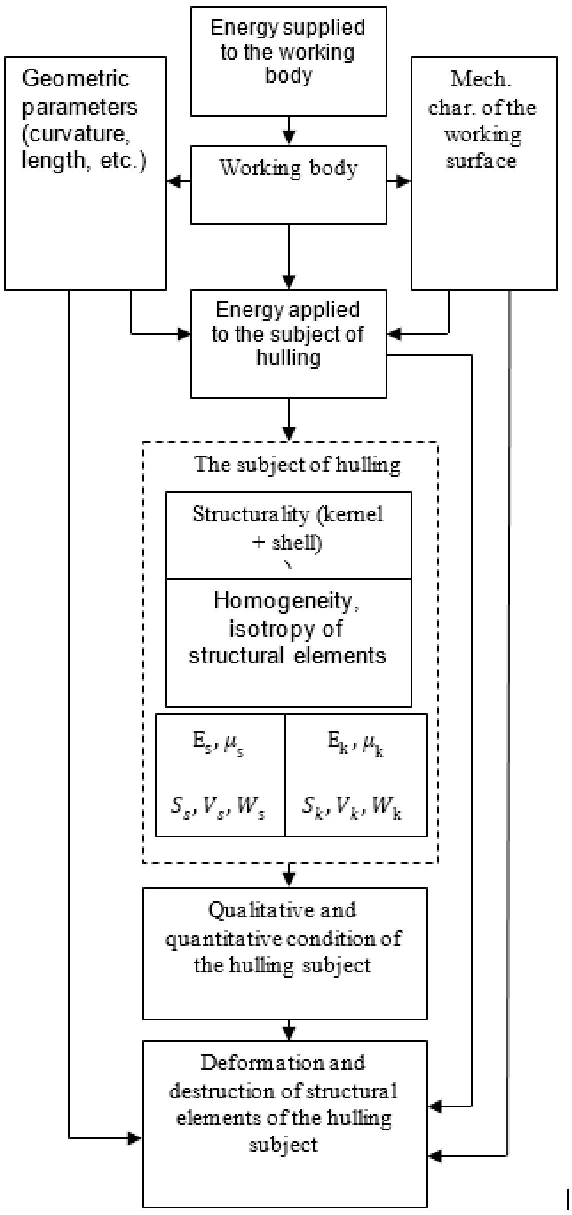

Fig. 1. Structure diagram of the hulling subject model

The destruction of the shell in the simulation is considered as its deformation to the supercritical stage and its collapse with the formation of cracks along the meridians of the sphere.

Based on the theory of shells, the potential energy of the grain shell of cereal crops, depending on the deformation, in the interaction with the working surface is determined by the following dependence:

$$U(h) = k_s h_s^{\frac{3}{2}}, \qquad (5)$$

where $U(h)$ is the potential energy of deformation of the fruit shell of the hulling subject as a function of deformation, $\frac{kg \cdot m^2}{s^2}$; k_s is the factor of proportionality, $\frac{H}{\sqrt{m}}$; h_s is the shell deformation, m.

The coefficient k_s depends on the strength characteristics of the hulling object shell, and the material of the working surface, as well as the curvature of their surface in the contact zone, is equal to:

$$k_s = 2{,}4\,\delta^{\frac{5}{2}} \frac{1}{D_s} ¿, \qquad (6)$$

where D_s is the shell diameter, m; δ is the shell thickness, m; E_s, E_{ws} are elastic modules of the shell and the working surface, N/m^2; μ_s, μ_{ws} are shell and work surface Poisson's coefficients.

During the interaction of the grain with the working surface, its total energy is equal to the sum of the kinetic energy of the deforming part of the structural elements $\left(\frac{m_g\, d\,h^2}{2\,d\,t^2}\right)$ and potential energy of elastic deformations $\left(k_s h^{\frac{3}{2}}\right)$. According to the law of energy conservation, we can write:

$$\frac{m_g \vartheta_a^2}{2} = \frac{m_g}{2} \cdot \frac{d\,h_s^2}{d\,t^2} + k_s h_s^{\frac{3}{2}}, \qquad (7)$$

where ϑ_a is the velocity of the hulling object at the beginning of interaction, m/s; m_g is the mass of the hulling object, kg.

Maximum strain value h_{sm} will take place when the relative strain rate turns to zero; hence we can write:

$$h_s = \left(\frac{m_g}{2k_s}\right)^{\frac{2}{3}} \cdot \vartheta_a^{\frac{4}{3}}. \qquad (8)$$

Let us determine the maximum value of the deforming force. To do this, we differentiate equation (5) by strain:

$$F_m = \frac{du}{dh} = 1{,}5\, k_s h_s^{\frac{1}{2}}. \qquad (9)$$

Then let us substitute formula (8) into the obtained equation. The value of the deforming force will be determined by the following equation:

$$F_m = 1{,}2\, k_s^{\frac{2}{3}} m_g^{\frac{1}{3}} \vartheta_a^{\frac{2}{3}}. \qquad (10)$$

During the theoretical study of the process of deformation and destruction of the shell we apply the first theory of the local limit state, the theory of maximum normal stresses. It is based on the following hypothesis: the limit state of the shell will occur when the normal stresses in the shell section in the area of contact with the surface of the working bodies reach the limit value σ_{max}. The force, directed along the centerline of the grain, acts on part of the shell for a time t and deforms the shell by the amount of *h*. This creates a contact area in the form of a circle and creates maximum stresses in the cross-section of the shell, which is determined by the following expression:

$$S_d = \pi d \delta, \qquad (11)$$

where *d* is the diameter of the contact area, m, (*d* = 2*r*); δ is the shell thickness, m.

These stresses are directed tangentially to the surface of the spherical shell along the perimeter of the contact site diameter.

The shell stability condition is written in the following form:

$$F_m^s = R_z(\sigma), \quad (12)$$

where $R_z(\sigma)$ is the projection on the axial line of the hulling object of the equipotential forces of internal stresses acting on the shell in the section with the maximum diameter d;

F_m is the maximum value of the external shock load; at this:

$$R_z(\sigma) = \pi d \delta \sigma \sin\theta, \quad (13)$$

where θ is the angle indicating the direction of normal stresses; σ is the value of normal stresses arising in the section of the shell, N/m^2.

Keeping in mind that $\sin\theta = \frac{d}{D_s}$, we write equality (9) in the following form:

$$R_z(\sigma) = \frac{\pi d^2 \delta \sigma}{D_s}. \quad (14)$$

To determine the diameter of the contact area d, we use the known approximate formula for determining the surface area of the ball segment $Dh = \frac{d^2}{4} + h^2$.

For the considered section of the shell of the hulling object when deformed by the value of h, the value of d^2 will be determined as:

$$d^2 = 4h(D_s - h). \quad (15)$$

Substituting equality (15) into equation (14), we obtain an expression to determine the projection of internal maximum stresses acting on the shell element in the considered section:

$$R_z(\sigma) = \frac{4\pi\delta h \cdot \sigma_e^s (D_s - h)}{D_s}. \quad (16)$$

The value σ_e^s in the expression can be considered as the sum of some stresses in the uniaxial stress state of the shell in the considered section, equivalent in effect to the stresses in the complex stress state of the whole shell. The effect here is understood as the occurrence of the limit state of the shell during deformation. Therefore, in further considerations we will use equivalent stresses instead of maximum stresses.

Condition (12), taking into account equality (9) and equation (16), will be written in the following form:

$$1{,}5 k_s h_s^{\frac{1}{2}} = \frac{4\pi\delta h \sigma_e^s (D_s - h_s)}{D_s}. \quad (17)$$

From here, let us express the equivalent stresses that may occur in the fruit shell during the interaction of cereal grains with the working surfaces:

$$\sigma_e^s = 0{,}12 \frac{k_s D_s}{\delta h^{\frac{1}{2}} (D_s - h_s)}. \quad (18)$$

The right part of the resulting equation includes the coefficient k_s, which characterizes the mechanical and geometrical parameters of the hulling object and the working surface. For a more complete analysis, we substitute expression (6) into equation (18) and after some transformations we obtain:

$$\sigma_e^s = 2{,}88 \frac{\delta^{\frac{1}{2}} \left(\frac{E_s}{(1-\mu_s^2)^{\frac{3}{4}}} + \frac{E_{ws}}{(1-\mu_{ws}^2)^{\frac{3}{4}}} \right)}{h_s^{\frac{1}{2}} (D_s - h)}. \quad (19)$$

Analysis of expression (19) shows that the stresses arising from deformation of the shell during interaction with the working surfaces depends on the physical and mechanical properties of the grain and the type of working surface. Consequently, by changing the physical and mechanical properties of seedcoat, flowering films of cereal seeds, as well as by changing the type of working surface of working bodies of hulling machines, we can determine the specific values of limiting stresses, under which the destruction of the shell occurs. Let's call these stresses critical stresses and denote by $[\sigma_s]$. Then the condition under which the shell breaks down will be written in the following form:

$$\sigma_e^s > [\sigma_s]. \quad (20)$$

Using expression (19) and condition (20), the allowable stresses under static and dynamic (impact interaction) loads for different conditions can be determined experimentally. However, it should be noted that during the impact interaction of grain with the working surfaces of hulling machines there is an effect of "delayed fracture". This effect is explained by the insufficient duration of time, during which the stresses resulting from the interaction act. The value of critical shell stresses is determined by static loading, where the loading time is long enough. Since in shock interaction, the load time span and, hence, the stresses are not large enough, it is necessary to increase the value of the stress in order to destroy the shell. Then the dynamic destructive stresses will be calculated by the following formula:

$$[\sigma_s]_{ws} = k_t^s [\sigma_s], \quad (21)$$

where $[\sigma_s]_{ws}$ is critical ultimate stresses of shell fracture during impact interaction with the working surface, N/m^2; k_t^s is the coefficient, which takes into account the duration of the stress-strain state of the shell during the dynamic action on the grain.

In an impact interaction, the stresses must reach a critical value if the shell is to collapse $[\sigma_s]_{ws}$. To determine the limiting impact velocity, we substitute expression (10) and (16) in condition (12). Then the condition of the limit state under dynamic influences taking into account (19) is defined by the dependence:

$$1{,}2 k_s^{\frac{2}{3}} m_g^{\frac{1}{3}} \vartheta_a^{\frac{2}{3}} = \frac{4\pi\delta h [\sigma_s]_{ws} (D_s - h)}{D_s}. \quad (22)$$

After transforming equality (22), it can be written in the following form:

$$\upsilon_p^0 = 19{,}47 \frac{\left[\left[\sigma_s\right]_{ws} h\left(D_s - h\right)\right]^{\frac{3}{2}}}{s D_s^2 \delta \rho_g^{\frac{1}{2}} \left[\frac{E_s}{\left(1-\mu_s^2\right)^{\frac{3}{4}}} + \frac{E_{ws}}{\left(1-\mu_{ws}^2\right)\frac{3}{4}}\right]} \quad (23)$$

The obtained expression allows us to calculate the impact velocity at which the critical stresses arise in the shell. To destroy the shell in dynamic hulling methods, the impact velocity must be greater than the value of the limiting velocity. Then expression (23) can finally be written in the form of the following inequality:

$$\upsilon_a^0 > 19{,}47 \frac{\left[\left[\sigma_s\right]_g h_s\left(D_s - h_s\right)\right]^{\frac{3}{2}}}{D_s^2 \delta \rho_g^{\frac{1}{2}} \left[\frac{E_s}{\left(1-\mu_s^2\right)^{\frac{3}{4}}} + \frac{E_p}{\left(1-\mu_p^2\right)^{\frac{3}{4}}}\right]}. \quad (24)$$

The obtained expression makes it possible to determine the region of impact velocity values at which the destruction of the shell occurs. However, it should be noted that the maximum velocity value should be limited to the impact velocity values at which the shell destruction begins.

As can be seen from the obtained inequality, the impact velocity in hulling methods should be greater than the right part of expression (24), which includes the limiting stress under which the shell destruction occurs, the elastic modulus, including geometrical and physical parameters of the shell. To determine specific values of velocity, it is necessary to conduct a number of experiments to determine geometrical, physical and strength characteristics of the fruit grain shell of cereal crops.

4 Conclusion

As a result of the research, a physical and mathematical model of cereal grains as the subject of hulling, consisting of two separate structural elements (spherical shell and spherical kernel), each of which has its own geometric parameters and rheological properties, mathematical dependences of destructive stresses of the shell and kernel during static and dynamic interactions with the working surfaces on their strength characteristics and geometric parameters have been developed.

The obtained theoretical dependences, taken together, constitute a mathematical model describing the process of destruction of the shell of cereal grains under static and dynamic influences. It can be used to simulate the collapse of sunflower seed shells in the production of seed oil.

The developed model enables to carry out computational experiments with the use of computers and software with a required set of given values of physical-mechanical and technological properties of the processed grains and construction-technological parameters of machines intended for destruction and separation of the shell. When using the appropriate software it is possible to visualize the process of shell fracture with obtaining a full frame-by-frame picture of distribution, magnitude, direction of loads and arising stress

In the future, to expand the practical usefulness of the obtained model, it is necessary to develop a model of destruction of the kernel of cereal crops (the most valuable part used as human food), which will allow one to identify the conditions of stresses, under which the destruction of the shell with the maximum preservation of its integrity occurs.

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