Ways to reduce mechanical damage of barley or mechanical processing

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Abstract. In the process of mechanized processing of batches of barley is its mechanical damage. As a result of the interaction of individual grains with the working bodies of machines, there are stresses exceeding the permissible, as a result of which they are destroyed. The article is devoted to the actual problem—the search for ways to reduce mechanical damage in the performance of technological processes of cleaning, post-harvest and pre-treatment. It is proposed to estimate the magnitude of stresses under force loading in barley grains by methods of elasticity theory, for which the barley grain is modeled in the form of a toroid. The adequacy of the real grain volume model is experimentally proved, the value of the elasticity modulus of barley grain depending on its moisture content is determined.

1. Introduction
The modern technological process of grain production, as well as many agricultural crops is impossible without the use of machines. However, during the mechanized processing grain batches as a result of interaction with the working bodies of machines, individual grains are damaged, i.e. mechano-damaged. The number of mechanically damaged grains in the batch (hereinafter—mechanical damage) according to [1, 2] reaches 60% or more, which significantly exceeds the limits defined by the standards on the quality of grain material and, accordingly, affects its further use. For seed grain in this case, there is a decrease in field germination and yield, for food deterioration of technological properties. In addition, steam grains with mechanical damage are less resistant to storage. Since it is not possible to completely eliminate the damage of grain during mechanized processing and transportation, the search for ways to reduce the amount of mechanical damage due to the perfection of the technological scheme of processing and technical means of its implementation is important and of national economic importance.

2. Problem statement
Let us consider as an object of study the technological process of mechanized processing of such an important crop as barley. Barley grains are mechanically damaged in contact with the working bodies of agricultural machines. This occurs due to a violation of the strength condition [3], [4], [5].

\[ \sigma_d = k_d \sigma_{st} \leq \sigma_b \]

where \( \sigma_{st} \) and \( \sigma_d \) – equivalent static and dynamic stresses arising in the grain, MPa;
\( \sigma_b \) – the tensile strength of the grain in compression, MPa;

\( k_d \) – the coefficient of dynamics depending on the speed of collision of grain with the working body and the magnitude of static deformation.

The idea of dynamic force loading of barley grain can be obtained on the basis of its static interaction with the working bodies of agricultural machines. The transmission of pressures in the contact points between the interacting bodies takes place on small sites. The body near such a contact site experiences a volumetric stress state (Fig. 1). Stresses and deformations at contact of bodies of different shapes are determined by methods of elasticity theory [5], [6].

![Figure 1. Stresses resulting from the contact of two bodies bounded by curved surfaces.](image)

Evaluation of the magnitude of mechanical stresses arising in the grain can be obtained at a known value of the load and knowledge of the shape of the grain. To estimate the contact stresses arising in the grain of wheat, peas, soybeans, buckwheat, corn different mathematical dependences were proposed [2], [9]. However, with the same force interaction with the working bodies of the machines, the stresses in the grains of these crops should obviously differ from the stresses arising in the barley grain, because it has a different form of the grain, and the proposed dependencies are not acceptable for such a case.

In accordance with the research task is to simulate the shape of barley and determine the dependence of stresses arising in it on the geometric and mechanical parameters of the grain.

3. Theory

To determine the stresses in the barley grain, we propose its geometric shape in the form of a toroid (Fig. 2). This figure is formed as a result of the eccentric rotation of the arc \( BCD \) circle with the center at the point \( O \) and radius \( R \) around the axis \( AZ \) (forming a circle), coinciding with the plane of the circle, the value of the eccentricity is equal to \( AO = r \) (guide circle).

We define the geometric parameters of the resulting shape.

Consider an arbitrary point \( M(x_0, 0, z_0) \) of a circle

\[
(x - r)^2 + z^2 = R^2
\]  (2)

When rotating around the \( AZ \) axis in the \( XOY \) plane, it will describe a circle

\[
x^2 + y^2 = x_0^2; z = z_0
\]  (3)

Because

\[
(x_0 - r)^2 + z_0^2 = R^2
\]  (4)

Opening the brackets and bringing like, get

\[
2x_0r = x_0^2 + r^2 + z_0^2 - R^2
\]  (5)

Taking into account (2), we obtain

\[
2\sqrt{x^2 + y^2} \cdot r = x^2 + r^2 + y^2 + z^2 - R^2
\]  (6)

By squaring both parts of the equation, we obtain the torus equation in the Cartesian coordinate system

\[
4\left(x^2 + y^2\right)r^2 - \left(x^2 + r^2 + y^2 + z^2 - R^2\right)^2 = 0
\]  (7)

This equation can be used to determine the length of the grain \( l \), which
\[ x = 0; y = 0; z = \pm \sqrt{R^2 - r^2} \]  

Therefore,

\[ l = 2z = 2\sqrt{R^2 - r^2} \]  

The same expression can be obtained from a right triangle \( AOB \)

\[ l = 2AB = 2\sqrt{BO^2 - AO^2} = 2\sqrt{R^2 - r^2} \]  

At the same time the diameter of the grains \( d \)

\[ d = 2AC = 2(OC - OA) = 2(R^2 - r^2) \]  

Solving together the equations (9) and (11), we obtain the values of \( R \) and \( r \)

\[ R = \frac{l^2 + d^2}{4d}, \quad r = \frac{l^2 - d^2}{4d} \]  

**Figure 2.** Barley grain in the form of a toroid (a design scheme)

The resulting figure of the toroid in relation to the grain of barley varieties *Omsky 95* in three projections and axonometric is shown in fig. 3
Determine the volume of the resulting figure as a body rotating around the z axis (Fig. 4). According to [9] the volume of the body of rotation is determined by the expression
\[ V = \int_a^b S(x)\,dz \]
where \( S(x) \) is the cross-sectional area of the resulting body of rotation by a plane passing through the point \( M \) perpendicular to the z axis
\[ S(x) = \pi x^2 \]

Taking into account
\[ r = 4 \]

We obtain the volume of toroid
\[ V = \pi R^2 \left( l - \frac{l^3}{12R^2} - 2r \cdot \arcsin \left( \frac{l}{2R} \right) \right) \]

Considering that the working bodies of agricultural machines, despite the large variety of their forms in the places of contact in General can be reduced to a plane or cylinder, consider the fig. 5 various most probable variants of static contacts of the proposed model of grain with the expected forms of working bodies of agricultural machines under the influence of compressive forces \( P \).
Damage to grain in the process of mechanized processing and transportation of grain batches is possible when the grain falls from a great height, for example, when unloading the vehicle on the concrete floor of the blockage pit of the production line (Fig. 5, a) or in contact with the cylindrical edges of the working bodies of machines (Fig. 5, b, c).

As a result of the interaction of bodies at the point of contact, an elliptical platform with the semiaxes $c$ and $t$ is formed. Knowing their values by the formula (15) is determined by the value of the greatest compressive stress

$$\sigma_{max} = \frac{3P}{2\pi ct}$$

where $P$ is the value of the compressive force, N.

The most dangerous point is located on the line of action of the force at some depth, depending on the ratio of the contact semiaxes $c/t$.

The values of $c$ and $t$ can be determined by the method for the generalized case of contact of two contacting bodies [5], [6]. According to this method, we first determine the main curvature radii $\rho_1$, $\rho_1'$, $\rho_2$, $\rho_2'$ and the angle $\varphi$ between the main planes of curvature:

- for the case of toroid contact with the plane $\omega$ (Fig. 5, a) $\rho_1=d/2; \rho_1'=R; \rho_2=\infty; \rho_2'=\infty; \varphi=90^0$;
- for the case of contact with the toroid cylinder at a parallel arrangement of the main axis of the toroid and the axis of the cylindrical edge (Fig. 5, b) $\rho_1=d/2; \rho_1'=R; \rho_2=R; \rho_2'=\infty; \varphi=90^0$;
- for the case of toroid contact with the cylinder when crossing the main axis of the toroid with the axis of the cylindrical edge (Fig. 5, c) $\rho_1=d/2; \rho_1'=R; \rho_2=\infty; \rho_2'=R; \varphi=90^0$.

Next, we determine the value of the auxiliary angle $\psi$ by the formula

$$\psi = \arccos \left( \frac{1}{\rho_1} - \frac{1}{\rho_1'} \right)^2 + \left( \frac{1}{\rho_2} - \frac{1}{\rho_2'} \right)^2 + 2 \left( \frac{1}{\rho_1} - \frac{1}{\rho_1'} \right) \left( \frac{1}{\rho_2} - \frac{1}{\rho_2'} \right) \cos 2\varphi$$

Thus

- for the case of toroid contact with the plane $\omega$ (Fig. 5, a):
ψ = \arccos \left( \frac{(2R - d)^2}{2R^2d + Rd^2} \right) \tag{17}

ψ = \arccos \left( \frac{(2RR_1 - dR_1 - dR)^2}{RdR_1(2RR_1 + dR_1 + dR)} \right) \tag{18}

ψ = \arccos \left( \frac{(2RR_1 - dR_1 + dR)^2}{RdR_1(2RR_1 + dR_1 + dR)} \right) \tag{19}

Further, knowing the values of the auxiliary angle, ψ, the corresponding tables [4, 5] by interpolation are the values of the coefficients m and n, which are necessary to determine the axes of the contact ellipse by formulas.

\begin{align*}
c &= m \cdot \sqrt{\frac{3\pi}{4} \left( \frac{P}{\rho_1 \rho_1' + \frac{1}{\rho_1'\rho_2' + \frac{1}{\rho_2}}} \left( \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \right) \right)} \\
t &= n \cdot \sqrt{\frac{3\pi}{4} \left( \frac{P}{\rho_1 \rho_1' + \frac{1}{\rho_1'\rho_2' + \frac{1}{\rho_2}}} \left( \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \right) \right)}
\end{align*}

where \( \mu_1 \) and \( \mu_2 \) Poisson ratios of contacting bodies, for a rough estimation you can take \( \mu_1 = \mu_2 = 0.3 \)

\( E_1 \) and \( E_2 \) – elastic modules of contacting bodies according to \[вЂ‹\text{Ошибка! Источник ссылки не найден.}\] for steel \( E_2 = 2 \times 10^5 \text{MPa} \).

Since the modulus of elasticity for the grain is much smaller than for steel \( E_1 \ll E_2 \), the value \( \frac{1-\mu_2^2}{E_2} \) can be neglected and the expressions (20) and (21) take the form

\begin{align*}
c &= m \cdot \sqrt{\frac{3\pi}{4} \left( \frac{P}{\rho_1 \rho_1' + \frac{1}{\rho_1'\rho_2' + \frac{1}{\rho_2}}} \left( \frac{1-\mu_1^2}{E_1} \right) \right)} \\
t &= n \cdot \sqrt{\frac{3\pi}{4} \left( \frac{P}{\rho_1 \rho_1' + \frac{1}{\rho_1'\rho_2' + \frac{1}{\rho_2}}} \left( \frac{1-\mu_1^2}{E_1} \right) \right)}
\end{align*}

However, in these expressions the value of the elastic modulus \( E_1 \) for grain is subject to experimental determination.

4. Experimental result

The value of the conditional diameter \( d \) is defined as the average of the dimensions of width \( b \) and thickness \( c \). Using the formulas (12) and (13), the values of radiiuses \( R \) and \( r \) are calculated using the values of length \( l \) and conditional diameter \( d \).

To determine the overall size of the barley grains were taken three varieties. The measurement results of dimensional sizes of the grains and the values of the parameters calculated by the above geometric dependencies (conditional diameter of grains \( d \), the radius of the forming a circle \( R \), the radius of rotation the guide circle (eccentricity) \( r \), the volume of grain \( V \)) are summarized in table 1.

Verification of the adequacy of the proposed model of the grain in the form of a toroid was carried out by measuring the volume of the real grain by briefly immersing five hundred grains in a measuring cylinder with water. The difference in liquid levels before and after grain immersion divided by the number of grains immersed is the average actual value of the grain volume. Measurement of the
volume of the grain was carried out in five-fold repetition. According to table. 1 the deviation of the actual volume of grain from the calculated one depending on the variety is about 10-15%.

In determining the $E_t$ barley grain was based on the technique [10], the essence of which was to compress the pre-prepared grains of different humidity between the tip of the indicator and the head of the screw micrometer special installation. The loading scheme is shown in fig. 5, a. With the help of an adjustable current source, loading and unloading was carried out at a constant speed of 4 N/s to the value of the force $P$.

### Table 1. Parameters of barley grain.

| Parameters of grain          | Variety Omsky 95 | Variety Sasha | Variety Acha |
|------------------------------|------------------|---------------|--------------|
| Weight of 1000 grains, g     | 42.4±0.73        | 52.7±0.81     | 50.5±0.75    |
| Length $l$, mm               | 9.26±0.46        | 9.99±0.51     | 9.65±0.60    |
| width $b$, mm                | 3.57±0.12        | 4.23±0.22     | 4.17±0.18    |
| thickness $c$, mm            | 2.76±0.11        | 3.24±0.16     | 3.26±0.17    |
| Conditional diameter of grain $d$, mm | 3.17           | 3.73          | 3.72        |
| Radius of the forming circle $R$, mm | 7.56           | 7.62          | 7.12        |
| Radius of rotation of the guide circle (eccentricity) $r$, mm | 5.98          | 5.75          | 5.33        |
| Volume of grain the calculated $V$, mm$^3$ | 40.2          | 60.7          | 58.1        |
| Grain volume measured $V$, mm$^3$ | 44.3±2.6     | 51.6±3.4      | 50.5±2.9    |
| Deviation, %                 | 10.20            | 14.99         | 13.08       |

As a result of contact static interaction with the use of a measuring magnifying glass, the values of the semi-axes of the ellipse $c$ and $t$ of the contact area were determined by the imprint on the pre-inserted between the grain and the tip of the colored paper at the value of the force $P$ before the moment of its destruction. Experimental values of the specified sizes $c$ and $t$ from humidity $W$ of barley of the Omsky 95 at power loading are presented in table 2.

### Table 2. Compression parameters of barley grain.

| Humidity $W$, % | The value of the force compressing the grain $P$, N | The dimensions of the semi-axes of the contact ellipse, $c$, mm | The area of the contact ellipse $S_{ca} = \pi c t$, mm$^2$ | The greatest stress in the center of the contact area $\sigma_{max}$, MPa | Elastic modulus $E_1$, MPa |
|-----------------|-----------------------------------------------|-------------------------------------------------|---------------------------------|-----------------|----------------|
| 7.1             | 44.85                                        | 1.37                                           | 0.87                           | 3.74            | 17.97          | 100.40         |
| 13.2            | 45.36                                        | 1.78                                           | 1.14                           | 6.37            | 10.67          | 46.30          |
| 19.3            | 46.43                                        | 2.34                                           | 1.59                           | 11.69           | 5.96           | 20.86          |
| 23.1            | 44.23                                        | 2.64                                           | 1.78                           | 14.76           | 4.49           | 13.84          |
| 28.1            | 36.56                                        | 2.83                                           | 1.88                           | 16.71           | 3.28           | 9.29           |
| 33.9            | 27.06                                        | 3.01                                           | 2.03                           | 19.20           | 2.11           | 5.71           |

The calculated value of the auxiliary angle $\psi$ for the case of fig. 5, a and made $\psi \approx 71^\circ$, the values of $m$ and $n$ according to [4], [5] $m=1.27, n=0.81$. The value of the total curvature
\[
\sum K = \frac{1}{\rho_1} + \frac{1}{\rho_2} + \frac{1}{R_d} = \frac{2R + d}{R_d} = 0.763m^{-1} = 763m^{-1}
\]

The values of the modulus of elasticity depending on the humidity will be obtained by substituting the corresponding parameters in (22) and (23)

\[
E_i = (1 - \mu^2) \sum K \cdot \frac{3\pi}{4} \left(\frac{m}{c}\right)^3 = (1 - \mu^2) \sum K \cdot \frac{3\pi}{4} \left(\frac{n}{r}\right)^3
\]  

(24)

The values of the grain elasticity modulus \(E_1\), as well as the contact area \(S_{ca} = \pi t\) and the highest stress \(\sigma_{\text{max}}\), calculated by the formula (15) obtained from the expression (24) are presented in table. 2.

For fig.6 presents a graphical dependences \(S_{ca} = f(W)\), \(\sigma_{\text{max}} = f(W)\), \(E_1 = f(W)\).

\[
S_{ca} = 10.166\ln W - 17.455
\]

\[
\sigma_{\text{max}} = 28.638e^{-0.078W}
\]

\[
E = 163.71e^{-0.10W}
\]

(25)

5. Discussion of results

The proposed model of barley grain in the form of a toroid corresponds to the volume of the real by about 85-90%.

It is noted that with increasing humidity, the value of the contact ellipse area during grain compression increases according to the logarithmic law, and the values of the greatest compressive
stress and modulus of elasticity decrease exponentially. In this case, the coefficient of reliability of the approximation is quite high \( \eta > 0.95 \).

The magnitude of the stresses generated in the grains of barley for mechanical processing depends on the curvature of the contacting bodies, their modules of elasticity, Poisson's ratios, moisture of the grain material, and the speed of collision of the grain with a working body.

6. Conclusion
To reduce mechanical damage to barley during mechanized processing is necessary:
- treatment at grain moisture of 15 to 20% (area of elastic deformations);
- monitor the condition of the edges of the working bodies, prevent them from sharpening;
- to apply the working bodies of material with a modulus of elasticity substantially less than steel;
- reduce the speed of collision of grains with the working body.

The use of the obtained theoretical dependences will allow the designer of agricultural machines at a known value of the compressive force to estimate the magnitude of the stresses arising in it.

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