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IMPACT ELEMENTS OF FEED GRINDER: A REVIEW

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Abstract

The article deals with the issue concerning the working bodies of technological equipment designed for grinding pieces and particles of feed raw materials. The most profitable feed raw materials are by-products and waste materials of animal origin, which have a valuable high-protein content. An alternative way of mandatory waste disposal is their processing, including mechanical grinding to obtain feed products. In the process of grinding, particular importance is given to the working bodies, with the help of which the raw material is directly divided into parts. In this case, the destruction of the feed material often occurs by means of impact. Impact phenomena have proven to be highly effective in the process of intense cracking and chipping, which leads to the desired separation of the crushed particles into smaller ones. However, it is found that crushers have insufficient efficiency of impact elements. The work analyzes the processes of impact grinding from the standpoint of a number of scientific hypotheses, theories, modeling, simulation, experience and approbation, presented in various scientific publications. When studying and improving the theory of impact, attention is paid to nonlinear problems, cracking, modernization of the theory of brittle fracture, diagrams of force changes during impact force, impact equations, wave theory of impact, peridynamic theory. It should be noted that the main scientific results are directly reflected in the improvement of the design features of hammers. It has been revealed that the main improvement in the design of impact elements is in the direction of increasing the efficiency of working surfaces and developing the combination of impact with cutting, abrasion and crushing.

Keywords: crushing, impact, hammers, destruction, crushers, feed, cracking, collision, shear.

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1. Introduction

The food security of the population largely depends on the volume and quality of meat, dairy, egg and fish raw materials, which can be obtained from farm animals, birds and fish with further processing into food products. To supply the population with this valuable raw material, it is necessary to provide farm animals, birds and fish with useful highly nutritious feed. One of the full-fledged components in mixed fodders is feed meal of animal origin [1]. Of particular importance in increasing the production of fodder flour is the use of all types of non-food raw materials, waste and confiscated goods from meat processing enterprises and farms, residues and by-products of public catering facilities (canteens, cafes, restaurants, etc.) [2]. The grinding of waste from dairy farms is widely used in the production of biogas [3], as well as in the preliminary and final grinding of feed products. One of the valuable sources of protein as feed is the keratin waste of farm animals [4]. Recently, a scientific concept has been developed and the principles of deep processing of collagen-containing raw materials of the meat industry have been formulated. The scientific foundations of models of hydrolysis in low-mineralized aqueous media of collagen-containing raw materials of the meat industry have been developed, which made it possible to create controlled technologies for the deep processing of by-products of meat and poultry processing [5]. It should be noted that in terms of chemical composition (amino acid content, balance of micro- and macro-elements), feather-down raw materials are a valuable source of nutrients and promising raw materials for the feed industry. Finding ways to rationally process feather-down poultry waste into feed additives is important [6]. To increase the production of fodder flour, it is necessary to expand the raw material base, mainly due to objects characterized by large-scale reserves and used irrationally. One of these objects are marine mammals (seals). The economic efficiency of seal processing is very low, since they are used only for obtaining skins and cover fat, the remaining meat and bone part of the carcass is not used. At the same time, marine mammals (seals) are one of the promising and biologically valuable objects of fishing for obtaining fodder products. They contain about 40 % of meat and bone tissues, characterized by complete proteins, a high content of easily digestible iron and minerals, and can serve as raw materials for the production of fodder meal [7]. As a low-value secondary raw material, protein-containing waste from the meat processing industry, in particular, the bones of slaughtered animals, which are currently processed, as a rule, into bone meal, can be considered. The traditional scheme of its production includes the following stages: grinding of raw materials, processing with steam or hot water, separation, drying [8]. In general, feeds of animal origin are characterized by increased nutritional and feed value, they are a valuable source of proteins and minerals in the feed rations of farm animals and birds [9].

In the technological scheme for the production of fodder flour of animal origin, the necessary processes are preliminary crushing and fine grinding [10]. When grinding dry feed raw materials, the cutting edges of the hammers work as a hammer working body and create a strong air flow [11]. For fine grinding of materials such as eggshells, bird and fish bones, hammer mills are used [12]. Crushers have low working capacity and insufficient efficiency of impact elements.

When studying impact phenomena during the grinding process, there is a clear change in the speed of the particles of the crushed material in a very small amount of time, the so-called impact time. The impact time of the working element on the particle of the crushed material is of great importance [13]. A typical example of impact phenomena is the impact of a crusher hammer on an egg shell or other feed raw material as a result of the preparation of feed flour [14]. Technologies based on the theory of impact are promising, as they allow to influence the object being processed with great effort [15]. The most effective destruction of the main solid materials occurs under shock loading [16].

In a hammer mill, the impact is either random or purposeful. In the first case, the impact objects at the moment of rebounding from the inner walls of the hammer crusher body are accidentally exposed to instantaneous forces. In the second case, in the technological process of fine grinding, the impact action of the hammers rotating on the axes is planned and carried out in a special way, as a result of which new objects are formed – particles of fodder meal. At the same time, the harder the crushed material, the more brittle and pliable it is to splitting.

The most common impact elements are crusher hammers, i.e. impacting bodies that are absolutely rigid and do not bounce off the system upon impact. The impact efficiency in the grinding process is often characterized by its purpose, i.e. obtaining more crushed particles. At the same time, the forerunner of separation, destruction [17–19] of pieces into particles by means of impact, is the formation of cracks and cracks in the crushed material, including larger cracks and cracks, which in turn will lead to the separation of the crushed piece into particles faster. Hence, cracking and slotting is the cause of softening.

The development of devices and assemblies for grinding, as well as impact elements, implies precisely a purposeful significance for improving the technique and technology of impact, as well as its high efficiency. Therefore, research in this direction is relevant and in demand. In this regard, the purpose of this work is to analyze and review scientific research on improving the impact elements of technological equipment for crushing and grinding.

To achieve this goal, the following tasks are solved:

– to analyze the existing theories and hypotheses of impact grinding processes;

– identify development trends in the field of designing impact elements of technological equipment for crushing and grinding.

2. Materials and methods

The work and research were carried out taking into account the search, analysis and synthesis of advanced and relevant information from open sources, including scientific articles, monographs, dissertations and abstracts of dissertations, books, journals, bulletins of patent offices, descriptions of patents for inventions and utility models, copyright certificates, collections and abstracts of scientific and practical conferences, reports and presentations of scientific seminars, information data from Internet portals, scientometric databases Web of Science, Scopus, ADB Data Library, ADB Publications, AGRIS: International System for Agricultural Science and Technology, ArXiv.org, Astana Civil Service Hub E-Library, Begell House, Bentham Open, Cambridge University Press Open Access, Cyberleninka, Directory of Open Access Journals, EBSCO eBooks Open Access Monograph Collection, EBSCOhost eBook EngineeringCore Collection, Elsevier e-Books Collection, Gale Reference Set, IEEE Xplore, InTech - Open Science Open Minds, Ope nStax, Oxford University Press Open, ScienceDirect, Wiley Open Access, Patentscope websites, Kazpatent, FIPS, EARO, EPO, WIPO, archives, libraries and reading rooms. In the process of analyzing scientific, technical and patent-licensed literature, the following were considered: trends in the development of devices for crushing and grinding, impact elements; designs of hammers, beaters, knives, impact-cutting and impact-split surfaces of the working bodies of crushers, grinders and mills; describes the dynamics of the development of theories of shock phenomena; the key developers of grinding devices are considered; analyzed the key segments and technologies for the use and grinding of feed raw materials, especially for the purpose of obtaining feed of animal origin. In compiling this review, a total of more than 190 research and development works were studied related to the issues of impact on crushed particles of feed raw materials. The main criteria for the inclusion of information data in this review were scientific research and design developments related to the use of original working impact bodies for grinding particles of feed flour, mainly for the period from 2002 to 2022, research on the application of theories of crack formation in various collapsible particles, wave theory, impact theory of modern theoretical mechanics, fracture theory, theory of mechanical vibrations, theory of mechanical impact, linear theory of viscoelasticity, non-local theory for conditions of an impermeable crack surface. The main keywords used in the search for scientific and technical information were the following: impact, crushing, grinding, hammers, beat, fodder flour of animal origin, destruction of particles, cracking, separation into parts.

3. Results and discussion

The issues of impact of bodies are the object of various research works, since the problems of designing modern crushers are often associated with the phenomena of the impact process. The main indicator of the impact process is the lightning-fast transformation of the velocities of the points of the given system.

Impact grinding was considered by the wave theory, the scientific works of which were published by work [20]. The wave theory of impact was first proposed by Businescu and Saint-Venant, which consists in the problem of the transverse impact of two solid bodies under the assumption that the total impact period is determined by the time required for the elastic compression wave to pass through the body and return back. However, the theory of Saint-Venant and Businescu does not take into account local plastic effects [21].

Hertz managed to establish by calculation the dependence of the magnitude of the contact force and the duration of the collision of bodies on their masses and velocities before the impact [22].

The impact is characterized by chance (objects of the impact process unplanned receive lightning pressure) or premeditation (impact is planned and implemented in advance). During the impact τ the instantaneous force changes from zero to the maximum value at the point $t^* \in [0, \tau]$, and then again to zero, i.e. this force is variable in time, but not explicitly expressed functionally. Graphically, the impact force is represented as an impulse crest, the peak of which corresponds to the maximum value of this force (**Fig. 1**) [23].

The features of the shock phenomenon are that shock pressures act during a short period of time. However, these pressures do not deviate from all other pressures. At the same time, the shortness of the exposure time directs the use of certain methods of study in the case of an impact phenomenon. Specifically, instead of Newton's equation of motion of a point $F = ma$, when considering an impact, it is more rational to use the law of change in the momentum of a point, which is briefly written and is called the basic equation of impact [24]:

$$m = (u - \nu) = S, \tag{1}$$

where $\nu = \nu_k(t)$ – point speed at the start of impact; $u = \nu_k(t+\tau)$ point speed at the end of impact; $S = S_k$ – momentum of forces acting during the impact.

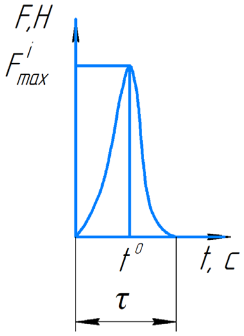


Fig. 1. Graphical representation of the impact force [23]

During the impact, the displacements of the points can be neglected. So, for any $t_1 \in [t, t+\tau]$, according to the momentum change theorem,

$$\nu_k(t_1) = \nu_k(t) + \left(\int_t^{t_1} F_k(t)\mathrm{d}t\right)\Big/ m_k. \tag{2}$$

Integrating equality (2) within the limits of t before $t+\tau$, let's obtain:

$$r_k(t-\tau) - r_k(t) = (\nu(t) + S_k^{av}/m_k)\tau, \tag{3}$$

where $r_k(t+\tau)$, $r_k(t)$ – radius vectors of the point at the beginning and at the end of the impact; S_k^{av} – average impulse value S_k in the interim $(t,t+\tau)$. Since the right side of equality (3) has the order τ then, according to the basic assumption of impact theory, it can be neglected and put $r_k(t+\tau) = r_k(t)$.

Let's now consider the translational motion of a body of mass m with a speed v, which makes up a certain angle (angle of incidence) to the normal of a fixed massive surface (obstacle) – an oblique impact.

Let's project the vector equality onto the normal and tangent to the surface (**Fig. 2**) [25]:

$$\begin{gathered} m(u_n - \nu_n) = m(u\cos\beta + \nu\cos\alpha) = S, \\ m(u_\tau - \nu_\tau) = m(u\sin\beta - \nu\sin\alpha) = 0. \end{gathered} \tag{4}$$

Then $u = \dfrac{\nu\sin\alpha}{\sin\beta}(*)$. And the recovery factor:

$$k = \frac{|\overline{u_n}|}{|\overline{\nu_n}|} = \frac{u\cos\beta}{\nu\cos\alpha} = \frac{\nu\sin\alpha\cdot\cos\beta}{\sin\beta\cdot\nu\cos\alpha} = \frac{\tan\alpha}{\tan\beta}. \tag{5}$$

Because the recovery factor $k < 1$, then the angle of reflection is greater than the angle of incidence. The angle of reflection is equal to the angle of incidence only in the case of an elastic impact ($k = 1$). Velocity modulus after impact in **Fig. 2**:

$$u = \sqrt{u_\tau^2 + u_n^2} = \sqrt{\nu_\tau^2 + k^2\nu_n^2} = \sqrt{(\nu\sin\alpha)^2 + k^2(\nu\cos\alpha)^2} = \nu\sqrt{\sin^2\alpha + k}. \tag{6}$$

In accordance with **Fig. 3**, a qualitative diagram of the non-linear dependence of the impact force is shown P_k in the contact section (diagram 1) depending on the approach α, when the impact force is described according to Hertz by the dependence $P_k = k\alpha^{3/2}$ [26]:

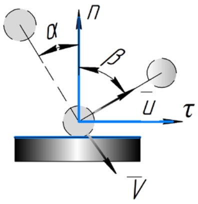


Fig. 2. Projection of vector equality on the normal and tangent to the surface [25]

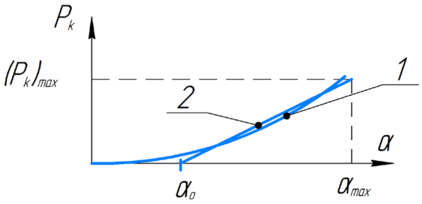


Fig. 3. Diagrams characterizing the change in contact force P_k from the approach of colliding bodies [26]: 1 – Hertz model, diagram; 2 – Biderman-Malyukova model

Biderman-Malyukova model (diagram 2) linearizes this dependence in such a way that the work of the contact force is equal when the colliding bodies approach each other, so that the maximum approach is equal $\alpha_{\max}$ and maximum values of contact force max $(P_k)_{\max}$.

The work of the contact force according to the Hertz model:

$$\int_0^{\alpha_{\max}} P_k \, d\alpha = \int_0^{\alpha_{\max}} k\alpha^{3/2} d\alpha = \frac{2}{5} k\alpha_{\max}^{5/2}. \tag{7}$$

The work of the contact force according to the Biderman-Malyukova model [27]:

$$\int_0^{\alpha_{\max}} P_k \, d\alpha = \frac{1}{2}(P_k)_{\max} \cdot (\alpha_{\max} - \alpha_0). \tag{8}$$

As $(P_k)_{\max} = k\alpha_{\max}^{3/2}$, then the work of the contact force according to the Biderman-Malyukova model is equal to:

$$\int_0^{\alpha_{\max}} P_k \, d\alpha = \frac{1}{2}(P_k)_{\max} \cdot (\alpha_{\max} - \alpha_0) = \frac{1}{2} \cdot k\alpha_{\max}^{3/2} \cdot (\alpha_{\max} - \alpha_0). \tag{9}$$

From equality of work:

$$\frac{2}{5} k\alpha_{\max}^{5/2} = \frac{1}{2} \cdot k\alpha_{\max-\alpha}^{3/2} \cdot (\alpha_{\max} - \alpha_0). \tag{10}$$

Let's find, that $\alpha_0 = \frac{1}{5}\alpha_{\max}$.

Rigidity of a linear elastic element k*, modeling contact interaction in the Bidermann-Malyukova model, is determined from the equality of the maximum values of the contact force $(P_k)_{\max}$:

$$k^*(\alpha_{\max} - \alpha_0) = k\alpha_{\max}^{3/2} k^*(\alpha_{\max} - \frac{1}{5}\alpha_{\max}) = k\alpha_{\max}^{3/2}, \tag{11}$$

where

$$k^* = \frac{5}{4} k\alpha_{\max}^{1/2}. \tag{12}$$

In accordance with **Fig. 4**, diagrams of the change in forces over time of the impact force in the impact section are presented for different amounts of concentrated masses:

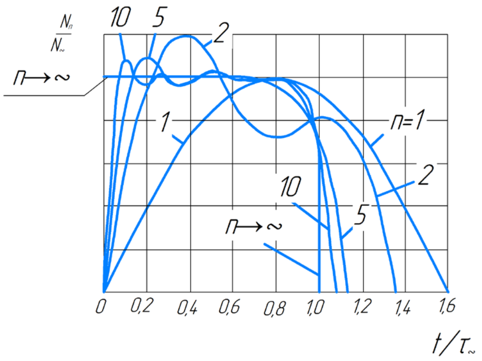


Fig. 4. Diagrams of changes in forces over time impact force in the impact section for different amounts of concentrated masses [28]

The theories of mechanical vibrations, together with the theory of mechanical impact, are selected areas of problems in mechanics and are of importance in the field of technology. Particular attention is paid to non-linear problems [29].

When studying the theory of impact, one should pay attention to such a phenomenon as crack formation in crushed particles. When considering cracking, one should pay attention according to Griffiths, quantum theory, which requires the adoption of reasoning rules called quantum reasoning, which is based on standard logic [30].

The article [31] analyzes Frenkel's theory of brittle fracture and attempts to modernize Griffith's theory of brittle fracture based on Frenkel's ideas. The sTable crack length according to Frenkel and according to the modernized Griffith equation corresponds to a local minimum of potential energy, which actually eliminates the singularity at zero crack length.

It has been noticed that there is an increase in the number of experimental observations-images showing intersonic and supersonic crack growth in the presence of shock waves. At the same time, it is clear that the high rate of crack propagation in these regimes is controlled by transferring the strain energy into kinetic energy, and not into surface energy or dissipation [32]. Of no small importance are the rebound processes of the crushed particles, which depend on the angle of impact [33]. At the same time, for each hammer of a hammer mill, there is a random static deviation, and for all hammers, there are phenomena of chaos with positions of relative rest in the range of a certain angle [34].

Researchers Mareks Smits, Eriks Kronbergs propose a hammer design with two mounting holes (**Fig. 5**). This design allows four options for fastening the hammer during its wear [35].

To fulfill the impact center condition [36] at point A at the end of the hammer, if the hinge is at point O_1, equation is used:

$$f(\zeta,r)=\left[\zeta-h+\frac{b\cdot h\left[\frac{h^2}{12}+\left(\frac{h}{2}-\xi\right)^2\right]-\pi\cdot r^2\left[\frac{r^2}{2}+(h-2\xi)^2\right]}{b\cdot h\left(\frac{h}{2}-\xi\right)-r^2\cdot\pi(h-2\xi)}\right]=0, \tag{13}$$

where ξ – distance from the end face of a rectangular hammer to the center of the hole, mm (**Fig. 5**); r_1, r_2 – hole radii, mm; h – hammer length, mm; b – hammer width, mm.

Based on this, it is recommended to design hammers in such a way that their collisions with the crushed particles take place in the center of impact of the hammer. Then the opening of the swivel joint of the hammer wears out less, the imbalance and vibration of the rotor of the hammer crusher are eliminated [35].

In [37], it was indicated that the effects of changes in the impact velocity and fracture toughness were studied. The path of the crack was successfully predicted with fixation of the branching of the crack. The results confirm the ability of the peridynamic theory to model crack growth in impact problems.

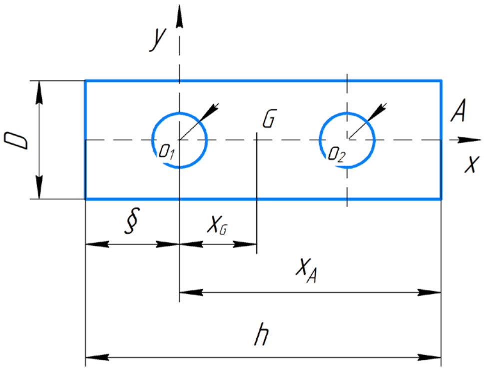


Fig. 5. Rectangular hammer with two holes [35]

In [38], the dynamic buckling of beams with cracks subjected to impacts was studied. Dynamic control equations for buckling of cracked beams are derived from Hamilton's principle using the first-order shear deformation theory.

Within the framework of the linear theory of viscoelasticity the problem of a dynamic transitional crack is considered. It is about a finite-length crack moving in a strip-like viscoelastic body under shock loading. In this case, the Laplace and Fourier transforms were used, and the resulting dual integral equations were reduced to the Fredholm integral equation of the second kind [39].

There is a well-known work [40], in which notes that the dynamic fracture behavior of brittle materials containing microcracks should be investigated when the material is subjected to impact loading. The effect of microcracks on the propagation of macrocracks that originate from the tips of notches in the Kalthoff-Winkler experiment, a classical impact problem, has been studied. In order to define predetermined microcracks in three-dimensional space, scientists have proposed a two-dimensional microcrack, as well as the definition of a plane in peridynamics based on constraints, which is a non-local form of classical continuum theory.

In [41] investigated the relationship between critical impact velocities for crack initiation and material properties for silicon nitride. All silicon nitride ceramics showed a Hertzian cone crack on impact and also showed a clear relationship with the Hertzian cone crack theory. In silicon nitride, which includes 30–50 micron needle-like grains, the growth of the Hertzian cone crack was suppressed due to the surface annular crack, and the expansion of the Hertzian cone crack was also suppressed.

In [42], cold and hot-cold shock tests were carried out to study the failure mechanism. The results showed that the thermal stress caused by thermal shocks eventually led to the expansion of the original crack. The main types of thermally induced cracks were intergranular crack, transgranular crack, aerodynamic crack, transverse crack, dendritic whisker crack, and mesh crack. It was found that the greater the temperature difference, the higher the thermal stress. Hot-cold shock can lead to more cracks and more extensive crack propagation than cold shock, which is accordingly considered to be advantageous.

It is pointed out in [43] that the propagation of cracks is due to a combination of a plastic process and an elastic process occurring as a result of brittle fracture of a dislocation-free zone. The model of the dislocation-free zone was used to describe the mechanisms of plastic fracture, as well as the transition from ductile to brittle. Based on the model, a brittle fracture mechanism was also proposed in the presence of crack tip deformation. Screening of the crack tip by dislocations in the plastic zone was discussed from the point of view of the local stress intensity factor.

In [44], the behavior of a Griffith crack in a piezoelectric material under an antiplanar shear load is studied using a nonlocal theory for the conditions of an impermeable crack surface. Using the Fourier transform, the problem can be solved using two pairs of dual integral equations. These equations are solved by the Schmidt method. In contrast to the previous results, it was found that there is no stress singularity and electrical displacement at the crack tip.

Fig. 6 shows the fracture force model for an elliptical crack with a type I three-point bend:

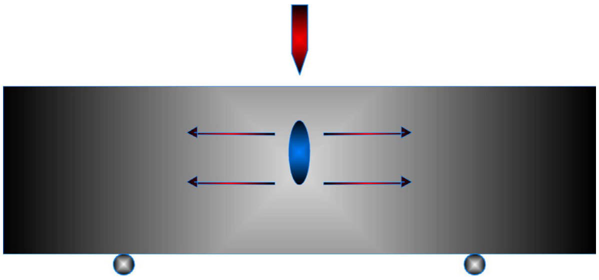


Fig. 6. Stress diagram for a three-point bending of an elliptical type I crack [45]

Assuming that the long axis of the ellipse is $2a$, the short axis is $2b$, and the coordinates of the local point are (c, 0), the parametric equation of a planar ellipse is given in the following form:

$$x = a \cdot \cos t,\ y = b \cdot \sin t. \tag{14}$$

In [46] studied the transient response of a saturated porous cylinder containing a crack and subjected to a suddenly applied normal load. The general equations of the Biot theory are used in the formulation together with the Laplace transforms and integrals to reduce the mixed boundary value problem to the solution of the Fredholm integral equation of the second kind. The results are presented and compared with the results for a dry environment in order to find out the effect on the dynamic stress intensity factor.

In general, the analysis of the operation of the crusher rotor revealed the following: the crushed material intensively hits the edges of the hammers due to high centrifugal acceleration. To increase the efficiency, the design of the hammers was changed by forming a toothed surface on the outer surface of the hammers (**Fig. 7**) of the four surfaces of each hammer, which made it possible to strengthen the working areas of the hammers and eliminate insufficiently effective impacts on the particles of the crushed material. The originality of this design is confirmed by a patent for the invention [47].

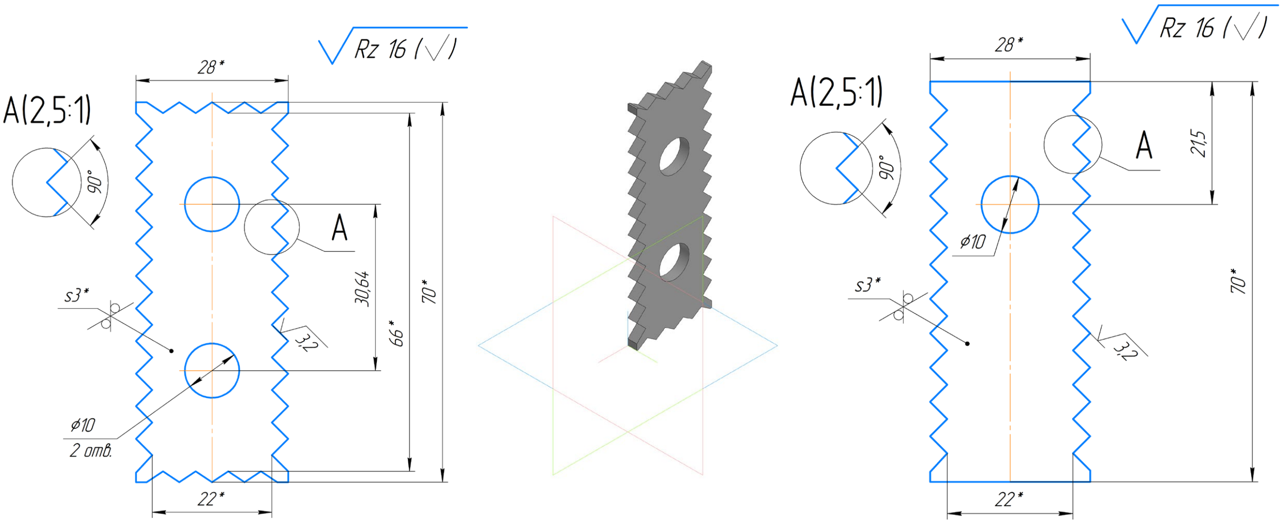


Fig. 7. Hammers with sharp-toothed surfaces [47]

This hammer is pivotally suspended on an axles (**Fig. 8**).

It is possible to fix up to five such hammers on the axles, between which washers are installed (**Fig. 9**). **Fig. 10** shows an assembly drawing of a single axle assembly with five hammers. The hammers are fixed on the axis with the help of a standard part – a cotter pin.

In [49], attention is focused on the impulses in the collision of raw materials with hammers and a rotor in a crusher. Particles of the crushed material, colliding with the pointed teeth of the hammer, according to the theorem on the change in the momentum, receive an impulse:

$$m(\nu_1 - \nu_0) = \int_0^{t_i} F(t)\,\mathrm{d}t, \qquad (15)$$

where ν_0 – impact speed of a particle on a toothed hammer; ν_1 – particle velocity after impact; m – particle mass.

The work of the impact force for the destruction of a piece of volume V is determined depending on the physical and mechanical properties of feed raw materials of animal origin for compression and the energy intensity of the impact destruction process. Using F. Kick's hypothesis, a formula for the work of the impact force is derived:

$$A = \frac{\sigma_c^2}{2} \cdot V, \qquad (16)$$

where σ_c – compressive strength of fodder bone raw materials of agricultural animals and birds; E – its modulus of elasticity.

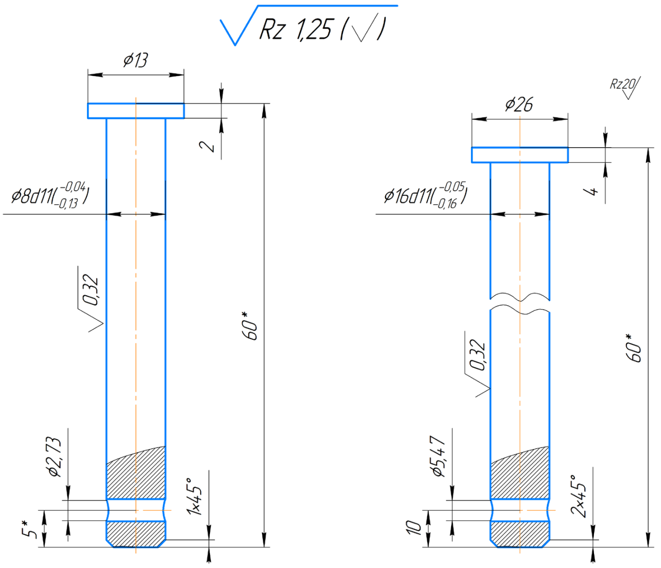


Fig. 8. Axes [48]

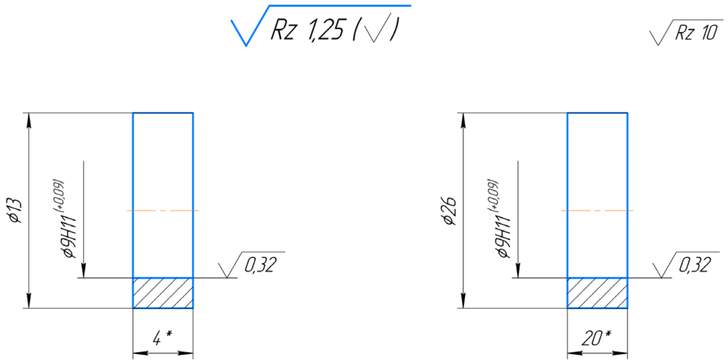


Fig. 9. Washers [48]

For example, for cattle bones $\sigma_c = 170–200$ MPa. Elastic modulus $E = 1.1$ GPa. Impact duration t_i depends on the magnitude of the deformation and on the depth of penetration of the hammer teeth into the bone Δ:

$$t_i = \frac{2\Delta}{\nu_i}. \qquad (17)$$

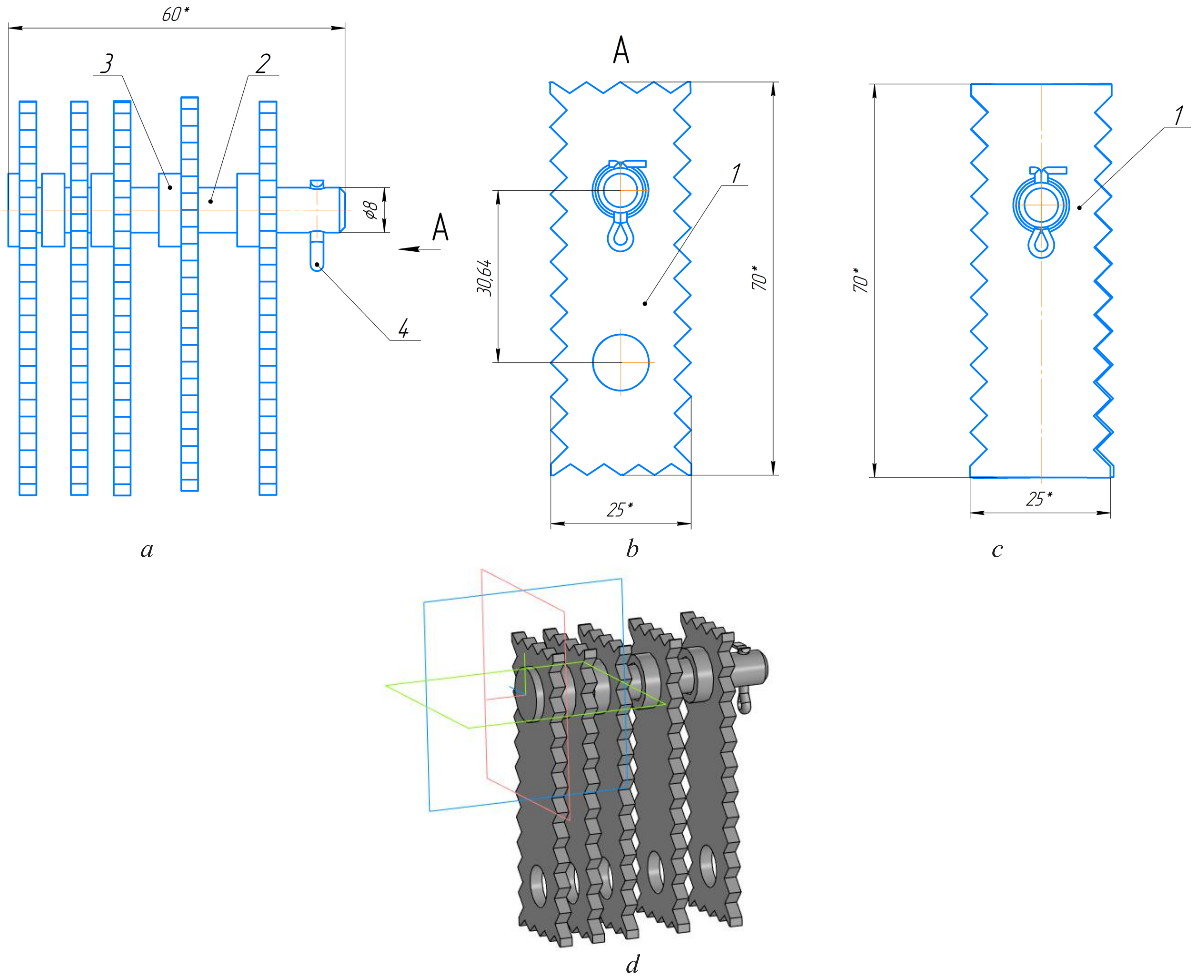


Fig. 10. Assembly drawing of a single axle assembly with five hammers [48]:
a – A series of hammers with teeth on all four surfaces, mounted on an axle; *b* – Hammer with teeth on all four surfaces with two hinge holes; *c* – Hammer with teeth on all four surfaces with one hinge hole; *d* – 3D model of hammers; 1 – hammer, 2 – axle, 3 – washer; 4 – cotter pin

Particle destruction work:

$$A=\int_0^{\Delta} F_i(S)\,\mathrm{d}S, \tag{18}$$

subject to the constancy of the impact force:

$$A=F_i\cdot\Delta. \tag{19}$$

Under this condition, the value of the shock impulse of the force will be:

$$\int_0^{t_1} F(t)\,\mathrm{d}t=F_i\cdot t=\frac{2A}{\nu_i}. \tag{20}$$

Thus, the work required to destroy the feed raw material with a direct blow depends on the speed of the hammer on the piece and the impact impulse.

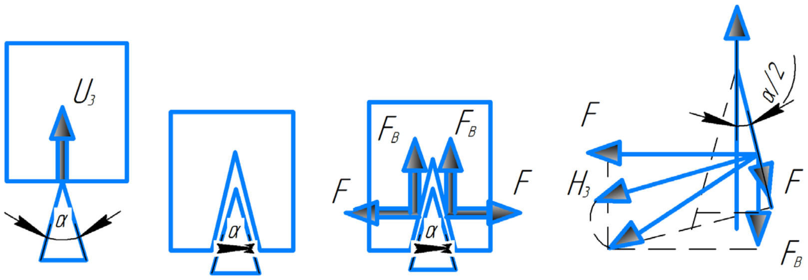
These conclusions are valid when the particle hits the tip, i.e. the impact will be central. In the case when a sliding impact occurs, the law of particle motion will look like this:

$$m\frac{d\nu}{dt}=F_i+\lambda\frac{\partial f}{\partial l}, \tag{21}$$

where f – the equation of the tooth surface in the selected coordinate system (in this case, the equation of the flat surface of the tooth); l – the direction of movement of the particle on the surface of the tooth.

In the study [50], a hammer with sharp-toothed edges was used. Consider the variant of the impact of the element on the sharp tooth of the hammer. Let a pointed tooth with an angle α at the top, it instantly acts on the crushed element with force U_3 (**Fig. 11, *a***). A crack is formed, the tooth is introduced into the crack, while the shape of the crack repeats the shape of the tooth. The force from the cheek of the tooth on the element is decomposed into a vertical component F_B, creating a crack plane and into a horizontal component that pushes the separated halves of the element in directions perpendicular to the fracture plane (**Fig. 11, *b***). Forces acting on one cheek of the tooth and mirror-symmetrical forces acting on the adjacent cheek are shown in **Fig. 11, *c***. Normal pressure on the cheek of the tooth H_3 and friction force F_3 give the total reaction force R. From the equilibrium conditions follow in accordance with **Fig. 11, *d*.**

It should be noted that in the feed industry and farms, the main grinding machine is a hammer crusher [51]. The article [52] proposes a constructive and technological solution that makes it possible to improve the quality of feed grinding while saving resources. In particular, it is noted that part of the transmitted force at the input of the cutting segment into the feed mass is extinguished by the arc profile of its planes, and due to the attachment plate to the working body, in the chopper operation, shock loads and vibration are significantly reduced, productivity is increased, and consequently increases its service life. The cutting segment (**Fig. 12**) of the feed chopper is made in the form of a blade, consisting of two planes 1, having an arcuate cutting edge 2, the planes of the cutting segment are connected by means of a fastener to the working body, made in the form of a rectangular plate 3 with holes 4:



a *b* *c* *d*

Fig. 11. To the conclusion of the action of the tip on the bone [50]: *a* – the beginning of the impact of the tooth on the crushed material; *b* – the force from the cheek of the tooth decomposes the crushed material into vertical and horizontal components; *c* – the action of forces acting on one cheek of the tooth, and mirror-symmetrical forces acting on the adjacent cheek; *d* – normal pressure on the cheek of the tooth and the friction force, which form the total reaction force from the equilibrium conditions

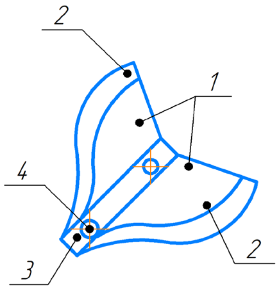


Fig. 12. Cutting segment of the feed chopper [52]

In [53], it is noted that in order to increase the maximum value of the degree of grinding, it is necessary to increase the relative speed of collisions between the particles of the crushed material and hammers. At the same time, it is known that the degree of grinding is influenced by various factors: the gap between the hammers and the deck or whips, the profile of the crushing chamber, the moisture content of the source material, the circumferential speed of the hammers, the residence time of the material in the working chamber, the location of the loading neck, the degree of opening of the unloading mouth, the position of the rotary shutters, etc.

In [54], the impact strength of knives was studied. To study the effect of the geometric parameters of chopper knives on the specific cutting work, a laboratory setup was developed (**Fig. 13**):

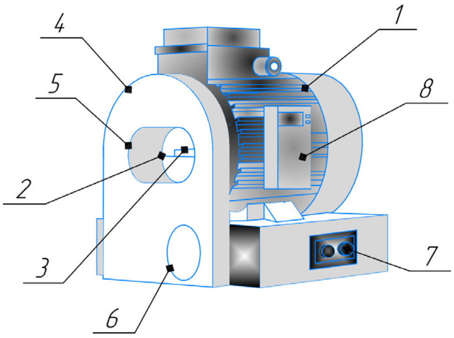


Fig. 13. 3D model of a universal installation for studying the process of cutting feed materials [54]: 1 – electric motor 2 – shaft; 3 – knife; 4 – protective cover; 5 – branch pipe for loading feed; 6 – unloading window; 7 – installation control buttons; 8 – device for measuring energy costs

The results showed that for hardened parts made of steel 45 it is higher than for knives made of steel 65G. The results show that knives made of hardened steel 45 have an impact strength of 9 J/cm^2 more than knives made of steel 65G.

In [55], a mathematical model was developed that makes it possible to determine the angle of deflection of the hammer in the process of impact interaction with a crushed piece in the working zone of the crusher. It has been proven for the first time that the ratio of the masses of the hammer and the crushed piece significantly affects the degree of crushing of the material by a free impact, while an increase in the fraction of crushed material leads to a decrease in the degree of crushing. Under the conditions of crushing materials by free impact, a mathematical model of erosion wear for the impact bodies of a hammer crusher was applied, corrected taking into account the distribution of the material and the angle of its impact with the hammer during repeated contact. It has been established that an increase in the mass of the hammer leads to a decrease in the wear of the impactor upon impact with the material, and an increase in the mass of a piece of material leads to its increase.

A structural and technological scheme of a horizontal impact crusher has been developed, which makes it possible to obtain a crushed product aligned in terms of granulometric composition. Analytical dependences of the grinding process are presented, which characterize the patterns of interaction of grain materials with the working bodies of a horizontal impact crusher, as well as rational design parameters and operating modes of a horizontal impact crusher [56].

It is noted in [57] that the equation of motion of a stamp upon impact with a layer of feed material coincides in shape with the equation of free damped oscillations, in which the damping coefficient, which reflects the dissipation of energy in the material layer, plays the main role. In the working chamber of feed crushers, a working body with a package of disks equipped with working elements of a hammer-segment type with segment-type counter-cutting decks should be used [58]. In some cases, it is possible to use the working body of a disintegrator-type grinder [59]. A technique for modeling the working process of a line of dry animal feed and working bodies from a grinder based on Markov chains is being used. A mathematical model of the influence of the main factors of the grinder design on the process of bone grinding has been constructed. An assessment was made of the values of the necessary forces for grinding the bone [60].

The work [61] presents analytical dependences for determining the specific area of the working bodies of the crusher, energy consumption for friction and ventilation in the idling mode of the crusher. As a scientific novelty, mathematical models of the influence of structural and regime factors on the performance of the hammer crusher working process are obtained, which make it possible to determine their optimal value. The specific area of the working bodies involved in the grinding process due to primary impacts by active elements – hammers, and secondary impacts on passive working bodies – decks and sieves, depends on a number of factors, the main of which are: physical and mechanical properties of the crushed material, the nature of the crushing surfaces and the parameters of the crushing machine grinding mode.

The work [62] considers vertical shaft impact crushers (VSI). In recent years, several mathematical models have been proposed for the VSI crusher. Experiments were carried out covering various feed rates, rotor speeds, types of distribution of feed by fineness. Model parameters such as K3 and T10 have been found to be particularly affected by key operating variables such as feed rate and rotor speed. Based on the simulations, it was concluded that the change in VSI behavior from a lower to a higher feed rate could be due to the transition from material fed predominantly to the rotor to an increase in the contribution of the cascade effect.

It is noted in [63] that when grinding grain with a moisture index higher than the ground state, there is a low efficiency of the impact crushing method due to increased plasticity of the material and an increase in the limiting deformation that the grain can perceive before destruction. A partial solution to this problem is possible through a combination of cutting and impact methods. In scientific research, the developed mathematical model of energy consumption by the crusher drive was used. As a result of theoretical studies, an analytical and graphical dependence of the energy consumption of the drive on the angular velocity of the crusher rotor shaft was obtained. Verification of the mathematical model through experiments showed a high level of its adequacy.

In [64], on the basis of the method of discrete elements, a rotor of an impact crusher with a vertical shaft was modeled. The effect of various guide plate angles on the rotor acceleration characteristics was studied by extracting particle velocity data. In the process of modeling, the shape of the particles was simplified and set as a sphere with a diameter of 10 mm. However, the destruction of particles was not taken into account to increase the efficiency of modeling. For the operation of the rotor, the speed of all particles must be taken into account. The higher the particle population speed, the greater their total kinetic energy and the better the effect of particle fragmentation. Therefore, the average particle population velocity can be used to some extent to study the rotor acceleration characteristics.

The work [65] presents a physical and mathematical model for designing and testing the annular armor of a vertical shaft impact crusher (VSI) to reduce energy consumption, improve grinding fineness and improve product quality. The design of VSI components has a significant impact on device performance. A suiTable contour of the impact segments of the annular armor has a significant impact on the grinding efficiency. In an empirical calculation, the impact angle can be far beyond the optimal impact angle of 90 degrees. In this work, the invention is based on providing the design of the impact segment of the annular armor with a high crushing effect.

In general, the considered mathematical models describing the impact grinding phenomena are summarized in **Table 1**, which indicates the disadvantages and advantages of each of these mathematical models.

In [66], analytical dependencies were obtained that characterize the processes of preparing pasty components based on meat and bone, fish and bone, and vegeTable raw materials, averaging moisture in binary compositions, compacting them, and drying the formed granules; mathematical models of the processes of obtaining meat-and-bone, fish-bone and vegeTable pastes, mixing with simultaneous averaging of moisture in binary compositions using a soy component, their compaction, granule molding and drying in the form of reliable regression equations with justification of the parameters of the proposed technical means and their modes of operation; a complex of technological and technical solutions made at the level of inventions that allow the implementation of these processes. The obligatory use of crushers and grinding devices is indicated as part of the technological schemes of a vacuum-drying plant for the production of fodder fishmeal, as part of the technological scheme of the press-drying method for the production of fodder meal. At the same time, the combination of processes is effective. The advantage is the combination of grinding and drying processes in one apparatus, which intensifies heat and mass transfer and ensures the production of fodder meal particles up to a standard granulometric size [67]. In the case of using feed raw materials that require additional sterilization and disinfection, several high-temperature devices, including boilers, dryers, and sterilizers, should be used in the processing line for processing animal waste. In this case, sterilization should be carried out last, i.e. after the grinding process in a crusher, which guarantees the production of fodder flour of high biological value [68]. In this case, in the process of heat and mass transfer, it is important to contact the dried particles in a variable gas flow [69]. At the same time, the operation of technological equipment for grinding and other technological processes is necessarily mechanized and/or automated. In this case, the rational and correct use of electric drives [70], optimal electrification and automated control with the possibility of varying the rotational speed of impact elements through a frequency converter have a great influence. In the field of adjusting the average size of the crushed particles, which is an important indicator in the preparation of feed, it is interesting to adjust the average size of the crushed particles. In [71], it is proposed to adjust the average size of the crushed particles using the number of rows of counter-hammers installed in the grinding chamber. In grinders of this design, the transportation of crushed feed is carried out by an air flow created by a hammer rotor. However, when grinding wet feed raw materials, rows of counter-hammers retain the wet mass, which does not contribute to obtaining a sufficient speed of the transporting mass in the grinding chamber.

Table 1
Disadvantages and advantages of mathematical models describing the phenomena of impact grinding

No.	Description of the mathematical model describing the phenomena of impact grinding	Disadvantages of the mathematical model	Advantages of the mathematical model
1	Mathematical model of the interaction of a hammer with sharp-toothed edges and crushed bone raw materials [50]	The depth of penetration of the hammer teeth into the crushed material has not been studied and the sliding impact has not been fully studied	The pointed teeth of the hammer instantly act on the crushed material, intensively forming cracks in it with a further break
2	Mathematical model of erosive wear for impact bodies of a hammer crusher [55]	An increase in the fraction of crushed material leads to a decrease in the degree of crushing	Allows to determine the angle of deviation of the hammer in the process of impact interaction with the crushed piece in the working area of the crusher
3	A mathematical model of the influence of the main factors of the grinder design on the process of bone grinding was built [60]	The influence of the step of arrangement of the working bodies has not been studied, which can significantly affect the degree of grinding	The values of the necessary forces for grinding the bone were estimated
4	Mathematical models of the influence of structural and regime factors on the performance of the working process of a hammer crusher have been obtained [61]	When considering hammers, due attention was not paid to the issues of reasonable location of hammers relative to each other	Allows to determine the optimal value of design-mode factors and indicators of the working process of a hammer crusher
5	Mathematical model of vertical shaft impact crusher (VSI) [62]	Significant effect of feed rate on the performance of the investigated VSI crusher	Ability to provide satisfactory VSI performance ratings
6	Mathematical model of energy consumption by crusher drive [63]	The low efficiency of the impact crushing method due to the increased plasticity of the material and the increase in the limiting deformation during grain grinding with a moisture content above the ground state	Combinations of cutting and impact methods. High level of adequacy of the mathematical model, in connection with which it can be used in the design of a disk vibrating crusher
7	Geometric model of rotors based on the design of an impact crusher with a vertical shaft [64]	Impact crusher front guide plate wear is the most serious	At the angle of the crusher guide plate, the maximum peak particle velocity in the whole process was relatively high
8	Physical and mathematical model for designing and testing the annular armor of a vertical shaft impact crusher [65]	The angle of impact between the particles of the original material and the segment of the annular armor in most cases is not determined	The maximum effect of size reduction and potential energy savings is about 8 %

In [72], the scientific novelty is the development of a methodology for calculating the parameters of impact loading during the destruction of wet materials containing physically bound water, which makes it possible to obtain rational technological, energy and kinetic parameters, taking into account the initial characteristics of products ground in an impact-reflective mill, as well as the requirements for the final product, the creation of an engineering methodology for calculating the combined crushing and drying processes in one apparatus. Theoretical and experimental studies of the process of destruction of single particles containing physically bound moisture by impact of low and high intensity are presented. stretching, internal pressures appear at the point of contact, which contribute to the removal of moisture, and the final moisture content of the destruction products depends on the strain rate, the initial particle size, and the physical and mechanical properties of the material [73].

In [74], as a scientific novelty, it was established that the extraordinary effect on the particles of the material to be ground, provided by the design of the rotary-vibration type grinder, makes it possible to increase the fineness of grinding and reduce the energy intensity of the grinding process. The theoretical dependence of the fineness of grinding on the parameters of the functioning of the design of a rotary-vibratory grinder has been established. The theoretical dependence of power costs on the geometric and kinematic characteristics of the grinder has been established. The dependence of the fineness of grinding on the geometric and kinematic parameters of the design of a rotary-vibratory grinder has been experimentally established.

The work [75] proposes the following sequence of operations for the preparation of meat and bone meal from bone: microwave drying, preliminary grinding, extrusion. Each of these operations is less energy intensive than some of the existing ones (energy consumption for grinding will be less, since the raw materials will be pre-dried), and the product quality will be higher due to the reduction in processing time.

In [76], it is proposed to combine such energy-intensive processes as drying and fine grinding in one unit; subsequent classification of the polydisperse mixture in order to return particles that have not reached a given size for final drying and grinding. Drying occurs when high shear forces are applied to the product. As a result, the process of grinding particles takes place. To study the influence of the temperature regime of processing on the degree of grinding, studies were carried out on mixing the paste without heat treatment and in the process of drying with mixing. According to the results of the research, it was determined that during the drying process in a horizontal paddle mixer with stirring, the product in the wet state undergoes grinding, and the main grinding of the product to fine particles occurs in the first 30...40 minutes of the process, while the product is in wet non-rigid state. Subsequently, the average fraction size remains practically constant, however, particle agglomeration is prevented. At the same time, the degree of grinding is influenced by the presence of heat treatment, since the change in the average particle size occurs more intensively. Regarding the combination of processes, it should be noted that the combination of grinding by cutting with the supply of the crushed material to the cutting pairs due to inertia forces can significantly reduce specific energy consumption [77].

From a general standpoint, the processes of destruction of food and feed raw materials by means of impact, cutting and compression are considered, taking into account the initial and final particle size, which is based on the hypothesis of a single approximation dependence of the minimum specific energy consumption. Analytically and experimentally, the possibility of intensifying the process of impact grinding due to the free oscillation of the working bodies and counter-impact units of crushers has been proved. A combined method has been developed for the destruction of raw materials with a heterogeneous, sharply different structure, based on its simultaneous longitudinal-transverse deformation, as well as a method for the gradual destruction of the structure of the crushed mass with the removal of crushed particles after each stage [78].

There are various technologies for obtaining fodder meal from the biomass of worms, the main technological operations of which are blanching, drying, and grinding. As protein additives, various types of feed meal of animal origin are traditionally used: meat and bone, meat, blood, bone, and from hydrolyzed feathers [79]. A cheaper and more accessible alternative to traditional types of fodder meal is earthworm biomass meal [80]. In terms of the content of essential amino acids, fodder meal from the biomass of earthworms is not inferior to traditional species. In addition, it contains long-chain fatty acids, minerals, a number of vitamins and is rich in nicotinic acid.

One of the ways to dispose of solid household and industrial waste is waste vermicomposting. Vermicomposting is a biological method of recycling organic waste (including industrial origin) by earthworms. At the same time, in order to reduce the time of bioconversion of organic wastes, their preliminary grinding is a prerequisite [81].

In [82], the actions of real crushers are compared with the simulation of crushers. The results show the shortcomings that are reflected in the further actions on the use of crushers. When modeling, it was found that the pressure of the air flow field gradually increased from the center of the rotor to the end of the crusher hammer [83]. In the process of studying the interaction of particles with each other, simulation and modeling methods should be used [84], especially when particles collide with each other.

The work [85] reports on the optimization of the parameters of a hammer crusher. It is shown that the initial grinding is more intense than the subsequent grinding. In [86], the result of the analysis of the sizes of crushed particles showed that the particle size decreased with an increase in the grinding speed.

It is pointed out in [87] that impact hammers are important components of impact crushers and are often short lived due to the high impact nature of their use. Wear-resistant alloys are welded to the surface of impact hammers to increase their service life. Most hammer crushers have a service life of 10 to 13 years and are low reliability objects. Basically, emergency stops occur due to the destruction of the rotor bearings. In the event of a sudden failure, unscheduled repairs and a decrease in production efficiency occur [88]. In a hammer crusher, when the rotor rotates, the hammers simultaneously swing around their axes. This wobble affects the movement of the rotor, causing vibration [89]. In [90], the effect of velocity in the annular space of the hammer and the shape of the hammer on energy consumption was studied. Considered and presented are factors and parameters that affect crushing in hammer crushers, such as unbalance and balance of the rotor. Improvement methods are proposed by means of prompt and timely balancing of the rotor in a hammer mill and on a balancing stand [91].

In practice, the following hammers have found application: the hammer of a hammer crusher, made in the form of a plate with a hole for its hinged suspension [92]; a hammer, in which, to increase the intensity of grinding, one end is made weighted, and the hammer is made as a single unit [93]; a hammer made in the form of a plate with flat side faces and one mounting hole, the axis of which is located at an angle of 900 to the side faces of the plate [94].

Many interesting hammers can be found in the invention environment. The hammer (**Fig. 14**) includes the base of the hammer 1, holes 2 for its hinged suspension and removable working faces 3. At the same time, the removable working face 3 has a figured protrusion 4 in the form of a dovetail for connection with the base of the hammer 1. Face 3 and the base of the hammer 1 are dead-ended on one side, and fixed with screw 5 on the other. During operation, the hammer strikes the material being machined with a removable working face 3 made of high-alloy steel [95].

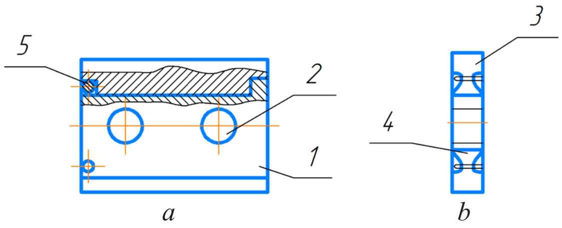


Fig. 14. Hammer: *a* – General view of the hammer; *b* – Left side view of the hammer [95]; 1 – the base of the hammer; 2 – holes; 3 – removable working faces; 4 – figured protrusion; 5 – screw

The hammer (**Fig. 15**) has a hanger 1 with a hole 2 for mounting on the rotor (not shown in the drawing) and a striker part 3 of the hammer, which can be tightened with a nut 5. The striker part 3 is connected to the hanger 1 through a sliding bearing 4 [96].

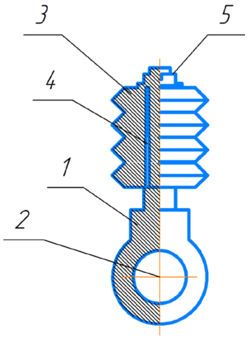


Fig. 15. Hammer crusher hammer [96]

Hammer 1 of rectangular shape (**Fig. 16**) contains holes 2 on the longitudinal axis of symmetry 3 and working sections 4 at the corners 5 of the rectangle with hardened end 6 and frontal faces 7 and 8. Slots 9, walls 10 and 11 of which form additional frontal faces, hardened adequately to other faces of the working sections. A hammer with a thickness «*S*» has a hardening depth «*t*» on all faces, the slots have a width «*a*» and a depth «*h*», while the slots are made decreasing in depth «*h*» to the longitudinal axis of symmetry 3, the width «*b*» of the jumpers between the walls adjacent slots. During operation, the product entering the crusher, colliding with the frontal edges and the crusher deck (not shown), is crushed, while wearing out the surfaces of these edges. Moreover, the parameters of the hardening depth «*t*» selected within the above limitations depending on the thickness «*S*» of the hammer, the width of the slots «*a*» depending on the method of hardening, the width of the bridges «*b*» between the slots depending on the depth of hardening contribute to an increase resource by optimizing the design parameters of the hammer. Hammers were tested with hammers without slots at the Luzinsky feed mill [97].

The hammer (**Fig. 17, 18**) consists of a plate 1 with a hole 2 for its articulated suspension on the axle 3, and samples 4 located on the working surface 5 of the hammer crusher hammer. Samples 4 are located on the working surface 5 of the hammer crusher at an acute angle α to the axis 3 of its hinged suspension. The crusher hammer plate 1 can be equipped with extensions 6 [98].

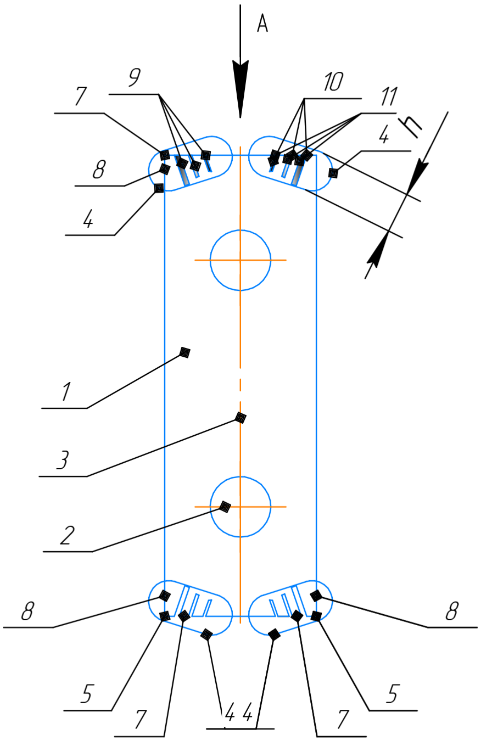


Fig. 16. General view of the hammer [97]

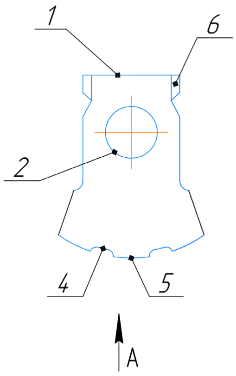


Fig. 17. The main view of the hammer [98]

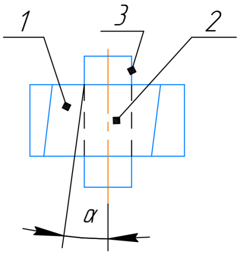


Fig. 18. View A of the hammer [98]

The crusher hammer (**Fig. 19**) is made in the form of a plate 1 with holes 2 for its hinged suspension, it contains hard-alloy inserts 3 [99]. The hammer (**Fig. 20**) contains a plate 1, along which there are holes 2 for its fastening, protrusions 3, the radii from the tops of which to the suspension point are equal, i.e., $r_0 = r_1 = r_2 = r_{optimal}$, and the speed of impact of the crushed material on these protrusions $\upsilon = \omega \cdot r$ will remain unchanged, hence the kinetic energy of impact remains unchanged [100]. The hammer (**Fig. 21**) contains a plate 1 with a hole for its hinged suspension, extensions 2 at the ends of the plate 1 and selections 3 located on the working surface 4 of the hammer [101].

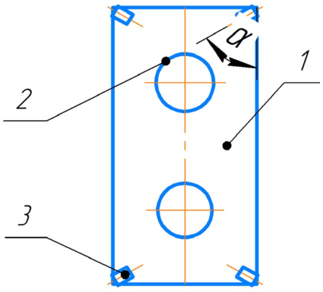


Fig. 19. Hammer [99]

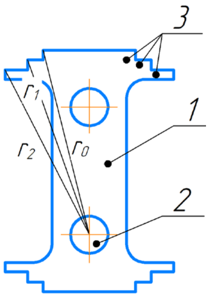


Fig. 20. Hammer [100]

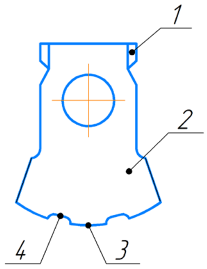


Fig. 21. Hammer [101]

The work [102] describes a patent for a hammer. The base of the hammer has a carbide embedded in the groove of the hammer. The device according to **Fig. 22** has a hammer base 1 and a striking surface built into the hammer base. The base of the hammer is made of hard alloy 2. The hard alloy is embedded in the groove 3 of the base part of the hammer. The groove is provided in the main part of the crusher. The groove is a dovetail or T-groove. The thickness of the impact plate can be increased so that the wear resistance of the hammer can be improved.

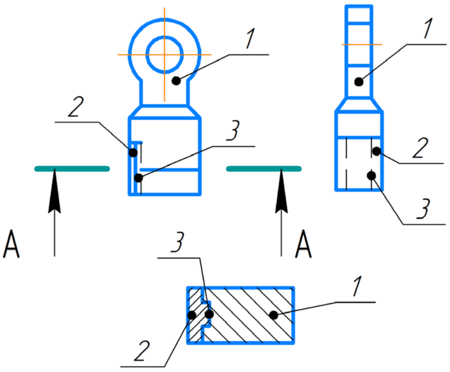


Fig. 22. Hammer [102]

The utility model claims a high-performance hammer crusher of a wear-resistant type. The utility model, thanks to the impact plate and impact head, can reduce the contact and surface of the hammer, at the same time, increase the pressure of the material, effectively improve the abrasion resistance of the hammer, and enhance the crushing ability of the hammer [103]. The utility model claims an impact crusher hammer with a composite plate and convenient installation [104].

As a result of the research, impact splitting hammers have been developed (**Fig. 23–28**). The hammer, in accordance with **Fig. 23**, is provided with rods, which increases the efficiency of the crusher. The originality of the hammer is confirmed by a patent [105]. The design of the hammer for grinding (**Fig. 24**) allows for an increase in productivity for the crushed material. The utility model relates to devices for crushing and grinding materials, mainly for crushing and grinding bone and meat and bone raw materials in the production of feed. The technical result is a compact and easy-to-maintain hammer for crushing and grinding, designed primarily for crushing and grinding bone and meat and bone raw materials in the production of feed, which helps to eliminate the rapid wear of the impact working surface of the hammer, increase the productivity of the crushed material and increase the efficiency of the hammer [106].

The toothed-comb hammer (**Fig. 25**) works in the following way. In the process of operation, the incoming material for grinding, colliding with the superhard teeth-combs 4 of the rotating hammers 1, is intensively crushed. During the operation of the hammer 1 and the wear of its working surface 3, the working surface 3 of the hammer 1 changes by changing the hole 2 for the hinged suspension of the hammer 1.

The technical result is a compact and easy-to-maintain toothed-rod hammer of a hammer crusher, designed primarily for crushing and grinding bone and meat and bone waste raw materials in the production of feed, contributing to an increase in the service life of the hammer, wear resistance of the working surfaces of the hammer and an increase in productivity for crushed material [107].

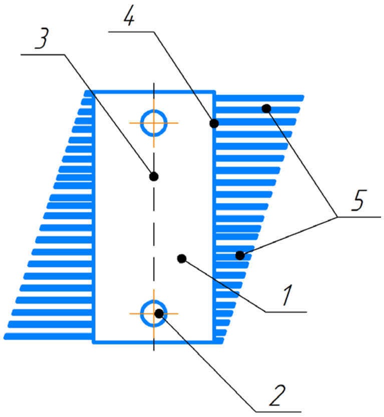


Fig. 23. Hammer for crushing and grinding [105]:
1 – hammer for crushing and grinding; 2 – holes for hanging the hammer on the axle;
3 – longitudinal axis of symmetry; 4 – working areas on two surfaces of a rectangular hammer;
5 – sharp-toothed rods of various lengths

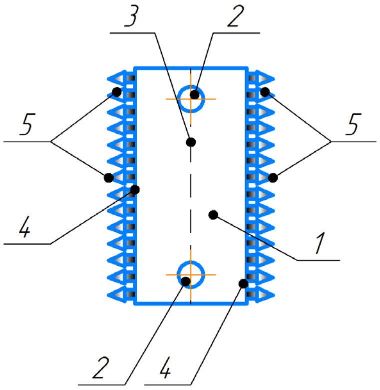


Fig. 24. Hammer for crushing and grinding [106]:
1 – hammer for crushing and grinding; 2 – holes; 3 – longitudinal axis of symmetry;
4 – working sections of the hammer; 5 – carbide wedges

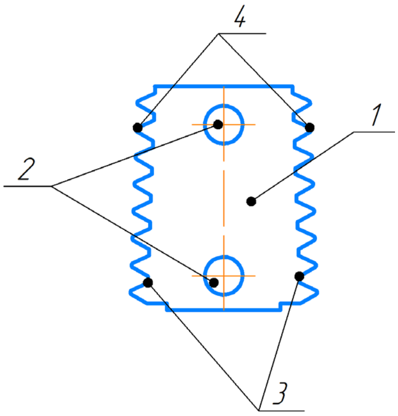


Fig. 25. Toothed-comb hammer of a hammer crusher [107]:
1 – toothed-comb hammer; 2 – holes; 3 – working surfaces on two surfaces of the hammer;
4 – superhard comb teeth

Machining is of great importance in the manufacture of crusher impact elements, including for improving the quality of the grinding surface and reducing vibrations of the technological system in order to limit the increase in cutting forces during the grinding process [108]. The turning method is also effective, which can be used to improve the quality and efficiency of turning processes by improving the surface quality, reducing the amplitude of cutting forces and increasing the material removal rate [109], including in the manufacture of impact crusher elements. **Fig. 26** shows photographs of percussion hammers. The originality of the designs is confirmed by the patent [110] and a patent for a utility model [111].

Fig. 26. Percussion hammers [47, 110]

The toothed-rod hammer of the hammer crusher is illustrated in **Fig. 27**. The toothed-rod hammer of the hammer crusher 1 works as follows. During operation, the incoming material for crushing and grinding, for example, bone or meat and bone waste raw materials, colliding with hard-alloy teeth-rods 4 of rotating tooth-rod hammers 1 is crushed and intensively crushed. During the operation of the toothed-rod hammer 1 and the wear of its working surface 3, in order to increase its service life, the working surface 3 of the toothed-rod hammer 1 changes by changing the hole 2 for hinged suspension of the toothed-rod hammer 1 [110].

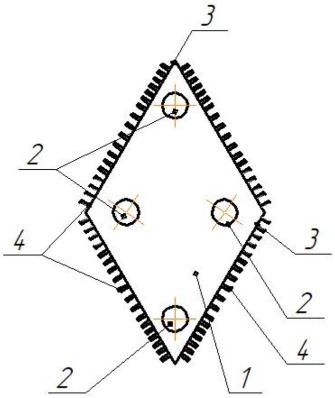


Fig. 27. Toothed hammer [110]

Fig. 28 shows the design of a toothed impact hammer. The utility model relates to devices for crushing and grinding materials, mainly for crushing and grinding bone and meat and bone raw materials in the production fodder.

On the basis of the above patents, it is interesting and practically significant to single out the classification of the designs of impact elements of crushers according to working surfaces, since the efficiency of breaking pieces and particles into parts often depends on the performance of the working surfaces and their impact. To study the designs of the working surfaces of impact elements, various technical solutions were analyzed and classified (**Table 2**).

In the process of classifying technical solutions, certain tasks of making managerial decisions appear, which are usually characterized by a high level of uncertainty. When solving this class of problems, it is necessary to take into account the external conditions for the implementation of the decisions made and the consequences that may arise in this case [112].

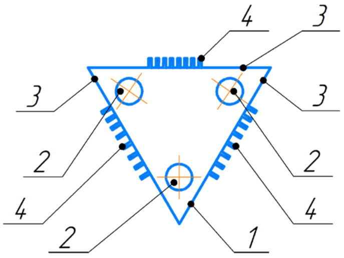


Fig. 28. Percussion hammer:
1 – hammer; 2 – holes; 3 – working surfaces; 4 – carbide rods [111]

Table 2
Classification of designs of working surfaces of impact elements of crushers

No.	Name of impact element of crushers	Description of the working surface of the impact element of crushers	Type of designs of working surfaces of impact elements of crushers
1	Hammer [95], hammer [102]	The removable working face has a figured protrusion in the form of a dovetail [95]. The striking surface is built into the hard metal base of the hammer. The groove is a dovetail groove [102]	The working surface of the impact element is of the dovetail type
2	Hammer [96], hammer [107], hammer [105], hammer [110], hammer [111]	Working impact part in the form of sharp teeth [96]. Working surfaces in the form of combs [107]. Working surface with toothed rods [105]. Working surface with teeth-rods on four sides of a rhombic plate [110]. Working surface with toothed rods on the bases of a triangular plate [111]	The working surface of the impact element has teeth
3	Hammer [97], hammer [99], hammer [100]	Corner working areas with frontal edges and slots [97]. Working surface with carbide inserts located at the corners of the plate [99]. Working surface with stepped protrusions located at the corners of the plate [100]	The working surface of the impact element has inserts at the corners of the hammer
4	Hammer [98], hammer [101]	Working surface with samples located at an acute angle to the suspension axis [98]. Working surface with selections [101]	The working surface of the impact element has a selection
5	Hammer [103], hammer [104], hammer [106]	Impact plate with impact head and wear-resistant type [103]. Working surface with composite plate [104]. Working surface with hardened pointed edges [106]	The working surface of the impact element has additional hardening

Based on the results of theoretical studies, a design scheme of a crusher with gear hammers was developed, which is part of a line for the production of bone feed meal from waste bone raw materials of agricultural animals, birds and fish.The originality of the production line is confirmed by a utility model patent [113]. The crusher is part of the production line shown in **Fig. 29**.

The operation of the production line for the preparation of broth, fat and feed flour is as follows. Bone waste is fed into power grinder 1, where preliminary grinding of bone raw materials by impact-cutting working elements occurs in sections, then through a magnetic metal catcher 2 along a screw conveyor 3, the bone raw material enters digesters 5, where it is boiled and degreased, by impulse pumps 4 from the digesters 5 suck fat through a pipeline 6 into a container 7 for collecting fat, then the defatted wet bone raw material from the digesters 5 enters through the hoppers 8 into the drainage device 9, where the broth is drained through the grate 10 into the tank 11 for collecting broth, then the raw material enters the press with a spiral mechanism 12 for maximum extraction of fat from the raw material into tank 13, after which the most defatted wet bone raw material enters the drying device 14, where a short-term high-temperature dehydration of the bone raw material by a stream of hot air takes place, then the defatted and dried bone raw material enters the crusher 15, *g* de finely crushed by means of rotating hammers and discs with serrated surfaces. The crushed product enters the hopper 16 for the finished product.

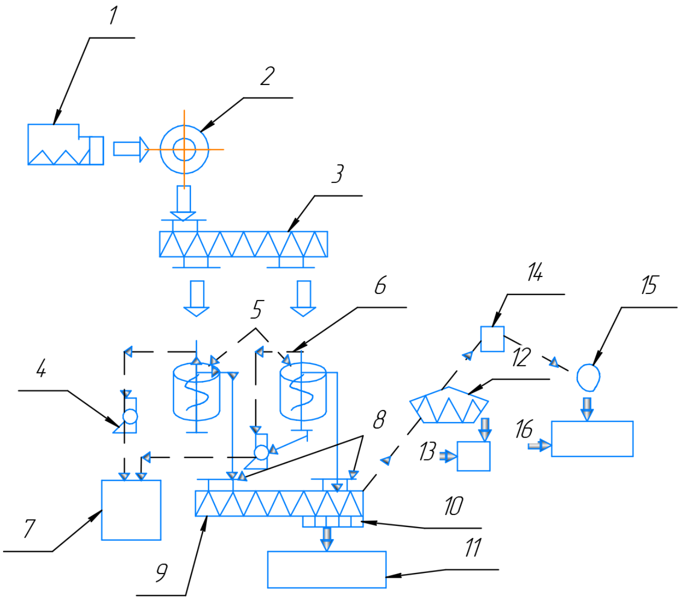


Fig. 29. Line for the Production of Bone Feed Meal from Waste Bone Raw Materials of Farm Animals, Birds and Fish [113]

4. Conclusions

Conducted studies on the selection and analysis of scientific and technical information regarding the working elements of crushers have established the following:

– the most effective way to increase the intensity of the impact action of hammers – the working bodies of crushers, is to improve the working surfaces with a guiding impact-splitting and impact-cutting action;

– features of shock phenomena are that shock pressures act during a short period of time;

– scientific hypotheses that offer designs of impact elements with sharp teeth, allow eliminating inefficient impacts of crushed raw materials on the edges of flat hammers;

– the main drawbacks are indicated that slow down the intensity of the process of grinding feed from waste of animal origin, in particular, the presence of passive zones on the working elements of crushers, insufficient performance of the working surfaces of hammers, the duration of crack formation in splitting particles of feed of animal origin, while the required work for the destruction of feed raw materials depends on the speed of the impact of the hammer on the pieces and particles of the crushed raw materials and the shock pulse. Mathematical models describing the phenomena of impact grinding are analyzed. The classification of designs of working surfaces of impact elements of crushers is given.

Based on the theory of Griffiths, it can be concluded that the separation of the material into parts occurs when the size of the crack and the magnitude of the load are combined. It can also be added here that the load depends both on the impact force and on the penetration of the working surfaces of the impacted element into the crushed material. On the basis of theoretical studies, patent-licensed search and analysis of scientific and technical information, analysis of the operation of crusher hammers, the designs of impact elements of crushers and grinders are generalized. Originality, novelty, inventiveness and industrial applicability of the developed technical solutions that intensify the process of impact grinding of fodder flour particles are confirmed by patents for inventions and utility models.

In conclusion, it should be noted the prospects of research and development work to further improve the working bodies of crushers and impact grinders, because. The preparation and use of feed raw materials is becoming increasingly in demand and relevant in the mixed feed and food industries.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

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