Agronomy Research **18**(3), 2117–2126, 2020
https://doi.org/10.15159/AR.20.191

Feasibility study of the grinding process of grain materials

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Abstract. For a comparative assessment of the effectiveness of various types of grinders of grain materials, various approaches are used. As the main criterion, the correspondence of the crushed material according to the particle size distribution can be taken as an indicator of the reliability of the grinding process. A comparative assessment of rotary crushers is carried out using the technical and economic indicator E_g, which is the ratio of total costs to the implementation of a given amount of work. Under the reliability of the grinding process, we have accepted the condition that the particle size distribution will comply with the requirements for agricultural feeding animals, which is possible while maintaining a rational gap between the stator and rotor riffles. The contradiction manufacturing techniques for the experiment are divided into: option No. 1 – steel 3 (HRC 10–12), option No. 2 – steel 45 (HRC 15–17), option No. 3 – hardened steel 45 (HRC 45–50), option No. 4 – steel 45 hardened and having a thin-film coating of FPH (finish plasma hardening), microhardness of 13 GPa. If reliability of the grinding process equal to 80%, wear on the fourth option, the cost was 1,171 rubles per ton, which is 16% lower than the cost of the first version of the production of a rotor crusher equal to 1,405 rubles per ton, respectively, this all speaks of the possible use of the proposed options for various forms of ownership of agricultural enterprises.

Key words: grain crushing, rotary crusher, working clearance, finished product quality, reliability of the grinding process, cutting element, wear resistance, feasibility.

INTRODUCTION

One of the main operations of preparing feed for feeding is the grinding of grain materials. Its implementation accounts for up to 75% of energy and 45% of labor costs. High quality and aligned size distribution of the crushed grain material are providing increase animal productivity and are the criteria it evaluating the performance of grinding devices (Lebedev et al., 2016).

Currently, hammer and impact centrifugal crushers are widely used in feed preparation lines, but during their operation, the content of the dust fraction increases to 30% with fine grinding, and under-crushed to 20% with coarse (Lebedev et al., 2012; Iskenderov et al., 2018).

The practice of operating hammer crushers has shown that there is a problem of excessive wear of the working bodies and low quality grinding of grain material, which decreases significantly with increasing humidity. The hammers of feed crusher have a minimum resource (their service life is from 72 to 300 hours). Resource of other working bodies is up to 2 times higher. However, this trend leads to the need for about 50 maintenance services per year. The data of the experiment we conducted in the agricultural production cooperative 'Kazminsky' in the Stavropol Territory, Russian Federation on the DM-10 hammer crusher are shown in Fig. 1. New sieve and hammers were installed on the it. Tests were carried out during the 35 days (every week 5 kg of crushed seed were selected). The weekly threshing was about 300 tons (Lebedev et al., 2012).

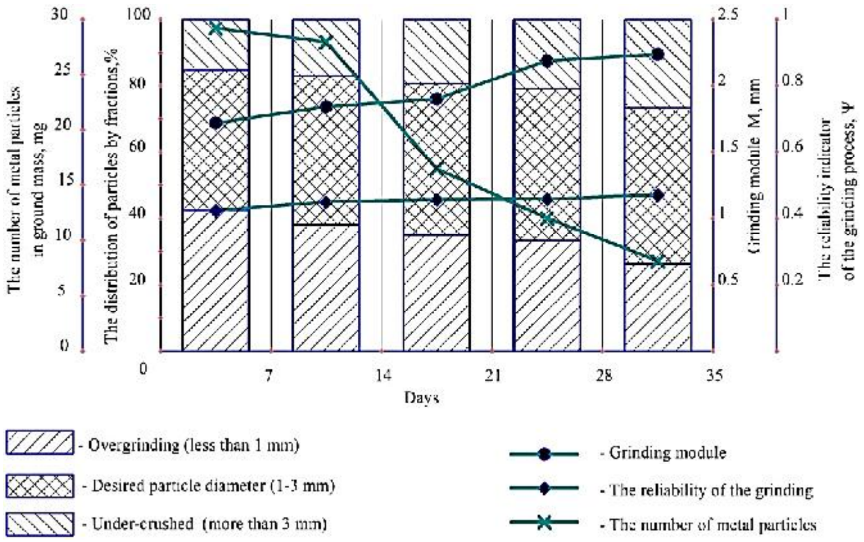

Figure 1. Experimentally determined indicators of grinding crushers DM-10.

As can be seen in the graph of Fig. 1, the average particle size in the first period of operation was 1.72 mm for a given grinding module M = 1.8–2.6 mm, i.e. the finished product contained more fine particles. Subsequently, an increase in the average particle size was observed. At the beginning of operation of the crusher the fraction of overgrinding was 42.4%, under-crushed 15.2%, at the end 26.2%, and 26.8%, respectively. This is due to the wear of sieve and hammers, which lost an average of 4.5 kg from the initial mass of 24.7 kg. For the entire experiment, the amount of ground mass corresponding to a given grinding module did not exceed 47%. And although the average particle size was in the specified range, in fact, only half of the feed mixture met the zootechnical requirements (Lebedev et al., 2012).

Thus, with the wear of the working bodies of the crusher, the degree of grinding of the starting material will also change. But the studies of grinders are mainly aimed at improving the structural and technological schemes of grinding, determining the optimal design or modes of its operation. Moreover, the analysis shows that the development of issues of increasing the durability of the working bodies of shredders is currently gaining particular importance.

In addition to everything, the question more often arises of the appropriateness of using and manufacturing hammer crushers, and way of replacing them with more modern designs that provide the best indicators with high-quality grinding (Sabirov et al., 2018; Thomas et al., 2018), for example, horizontal rotor crushers (Patent EA 026179, 2017).

The development of new and modernization of existing designs of crushers to provide animals with high-quality feeds is becoming an increasingly popular and urgent task against the backdrop of an annual increase in food prices. At the same time, there is a need to create new, more informative methods for evaluating grinding, both from the qualitative and the technical and economic aspects of this important technological process (Lebedev et al., 2011; Tumuluru et al., 2014; Sabirov et al., 2019).

MATERIALS AND METHODS

Experiments on grain refinement winter wheat were carried out on a horizontal rotary crusher produced in the training workshop of FSBEI HE 'Stavropol State Agrarian University'. The design of the crusher without changing initials parameters correspond, description in the (Lebedev et al., 2018; Iskenderov et al., 2019) and shown in Fig. 2.

Clarification of rational technical and economic indicators was carried out by performing a cutting element 5 of various structural materials. To carry out the experiment were made 3 cutting element with a length of 0.06 m. Each of them (Fig. 3, a) consisted of 4 independent segments of the same size, they are put on the rod base. These segments different depending on the type of steel grade and its processing technologyare divided into: Option No. 1 – St3 (HRC 10–12), Option No. 2 – Steel 45 (HRC 15–17), Option No. 3 – Steel 45 hardened (HRC 45–50), Option No. 4 – Steel 45 hardened and having a thin-film coating of FPH (finish plasma hardening), microhardness of 13 GPa. The segments, as shown in Fig. 3, b, were marked on the back (number of the experimental group from 1 to 3) and side (number of the type of manufacturing technology from 1 to 4).

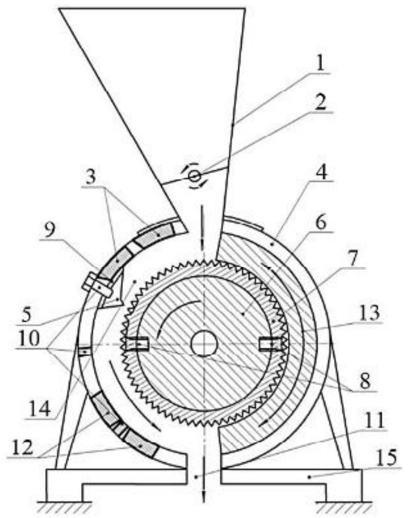

Figure 2. Scheme of a prototype rotary crusher: 1 – receiving hopper; 2 – damper; 3 – plugs in add. places of a loading window; 4 – a stator; 5 – cutting element; 6 – a rotor; 7 – a removable surface of a rotor; 8 – fastenings of a surface of a rotor; 9 – a lining for variation of a backlash; 10 – fastening and caps in add. locations of the counter-blade; 11 – discharge hopper; 12 – plugs in add. places of unloading; 13 – limiting lip; 14 – crushing chamber; 15 – frame.

The replaceable rotor surfaces of the prototype crusher were made of hardened Steel 45, with a hardness of HRC 45–50, their diameter was $D = 0.1$ m, and their length $l = 0.06$ m. The geometric parameters of the rotor riffles for grinding wheat were as follows: the number of riffles on the rotor is 38, with a pitch of t = 8 mm and the height of the riffle h = 1.2 mm, the angle of the riffle tip is 60°, and the wall angle 15° (Fig. 3, c) (Iskenderov et al., 2018; Iskenderov et al., 2019). During operation of the rotor crusher to maximum wear, an increase in the gap occurs between the rotor and cutting element, which, with the corresponding operating time, also causes a process disruption in the form of crushed grain material that does not meet the specified quality.

Figure 3. General view of: the cutting element (a), markings its segments (b) and the grinding zone in a horizontal rotary crusher (c).

To determine the probability of failure-free operation of the rotary crusher, we establish the relationship between its reliable and unreliable applications. Therefore, for the subsequent evaluation of the grinding process, an indicator of the actual grinding result was used. The grinding process is reliable provided that the particle size distribution meets the specified requirements for feeding livestock and poultry. Then, as an unreliability of the process, the appearance in the finished product of non-crushed and over-crushed grain fractions was considered.

Under normal operating conditions, the rotor crusher in question does not produce more than 5% of substandard products. In this case, the detection of undestructed wheat grains occurs with a gap between the stator and the rotor having more than 0.8 mm. This is due to the wear of their working surfaces, primarily the cutting element, which perceives several times more impacts per revolution of the rotor.

One indicator of equipment reliability is the probability of uptime. Considering the grinding process, based on the theory of reliability, we take that the under-crushed grain material is a failure of the system:

$$P(g) = 1 - F(g), \quad (1)$$

where $P(g)$ – the probability of uptime; $F(g)$ – the probability of failure or the occurrence of a under-crushed grain.

Fig. 4 shows the dependence that characterizes the changes in the main characteristics of the process of grinding grain in a rotary crusher.

As can be seen in the Fig. 4, grind with the observance of the required quality (for a specific grinding module) is characterized by almost 100% process reliability, that is, up to the section with the value of W_0. With further operation of the grinder, the probability of failure increases, which is characterized by the formation on the graph of the zone with a violation of the quality of grinding. At the same time, the probability of failure-free work begins to decline.

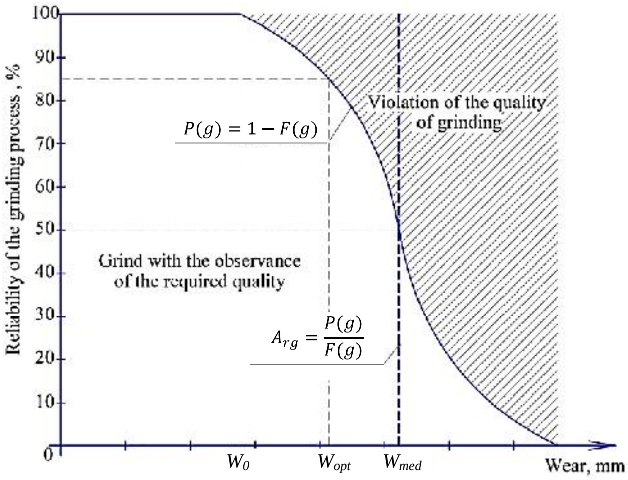

Figure 4. Theoretical probability of failure-free operation of the rotor crusher depending on the wear of the rotor and stator.

Any crusher has a state of equilibrium – the optimum reliability of the grinding process. After reaching and overcoming this boundary, operability drops and it is advisable to carry out preventive or scheduled maintenance to restore it.

Depending on the operating conditions, different requirements can be applied to the quality of grinding of the grain material, that is, a different value of the process reliability. For example, with an average level of wear of W_{med} work surfaces, which corresponds to the reliability of the grinding process of 50%, the crushed grain will contain both large fractions and very fine particles of the finished product. If their separation is carried out, the first (large) fraction can be used as feed for poultry, and small for pigs. However, often modern producers tend to use fast and productive methods of animal husbandry without intermediate feed preparation operations, as this entails additional energy and time costs.

So, the higher the reliability of the process, the more products of a given quality will be generated by the crusher, and the more preventive work will be required to maintain a given level of wear resistance of work surfaces. We take the optimal gap size for the W_{opt} rotary crusher, which meets the specified requirements for the quality of the crushed product and 85 ± 5% process reliability. For a more accurate and informative monitoring of the process reliability, we use the indicator of the actual result of the A_{rg} process (Lebedev, 2011). Using this indicator, we get:

$$A_{rg} = \frac{P(g)}{F(g)} \tag{2}$$

where A_{rg} – indicator of actual result of grinding process.

When calculating the reliability indicators of the rotor crusher, variation coefficients are used, which make it possible to choose the distribution law (normal or Weibula). The calculations were performed automatically in the MSExcel environment, based on the quality indicators obtained during operational tests of the rotary crusher.

For a comparative assessment of the effectiveness of various types of grinders of grain materials in practice, various approaches are used. A feature of our approach is the condition for an objective assessment of various types and types of grinders according to the quality of the grinding process, which is the *purpose* of these machines. Such an indicator, in our opinion, is *the reliability of the process being implemented*. The main criterion in assessing the reliability index of the grinding process is the *goal function*, that is, *the whole crushed mass must correspond in terms of particle size distribution to the given module and degree of grinding.*

A comparative assessment of rotary crusher is carried out using the technical and economic indicator E_g, which is the ratio of the total costs C_t of a predetermined space of work S_w and is determined by the formula:

$$E_g = \frac{C_t}{S_w} \tag{3}$$

The total cost of performing a given amount of work S_w can be determined by the formula:

$$C_t = C_m + C_l + C_e + C_{pw} \cdot k \tag{4}$$

where C_m – manufacturing cost; C_l – the cost of labor when grinding the mass of grain; C_e – the cost of energy consumed by grinding grain mass; C_{pw} – costs of preventive work; k – number of preventive work.

In view of the above, additional prophylaxis must be carried out upon reaching the rejection wear of the cutting element of rotor crusher W_{opt} corresponding to the reliability of the technological process 80–90%. It should take into account the additional costs, related to the elimination of the C_Δ revealed deviations in the grinding and used for additional crushing volume of products $S_{w\Delta}$ not corresponding task parameters.

Feasibility study criterion E_g cereal material grinding process at maximum wear working surfaces of the rotor and a cutting element must consider violation process and compensation additional costs for bringing the entire predetermined amount of work to the required quality. In this case, its value can be determined from the expression:

$$E_g = \frac{C_t}{S_w - S_{w\Delta}} + \frac{C_\Delta}{S_{w\Delta}} \tag{5}$$

Reducing the scope of work $S_{w\Delta}$ does not match the standards of the grinding is possible during timely preventive maintenance or by reducing wear of the cutting surface during the operation of the crusher. To calculate the basic indicators of costs, generally accepted methods of economic calculation are used to evaluate agricultural technical means. The total cost values may differ taking into account depreciation and costs different for each country and other indicators associated with the characteristics of certain industries, so we did not specifically take them into account. First of all, the feasibility study presented is aimed at identifying the possibility and profitability of increasing the reliability of the grinding process through the use of highly wear-resistant structural materials, taking into account the costs of their use.

RESULTS AND DISCUSSION

The analysis of the experimental results in Fig. 5 showed that the wear of the cutting element during running to its limit value (resource), on average, amounted to W = 1.26–1.48 mm. These data correspond to the values of wear, which are determined in real operating conditions. When evaluating the efficiency of the grinding process according to the proposed method, the reliability indicator is $P(g)$ = 10–25%, and the actual result indicator is extremely low – A_{rg} = 0.1–0.3.

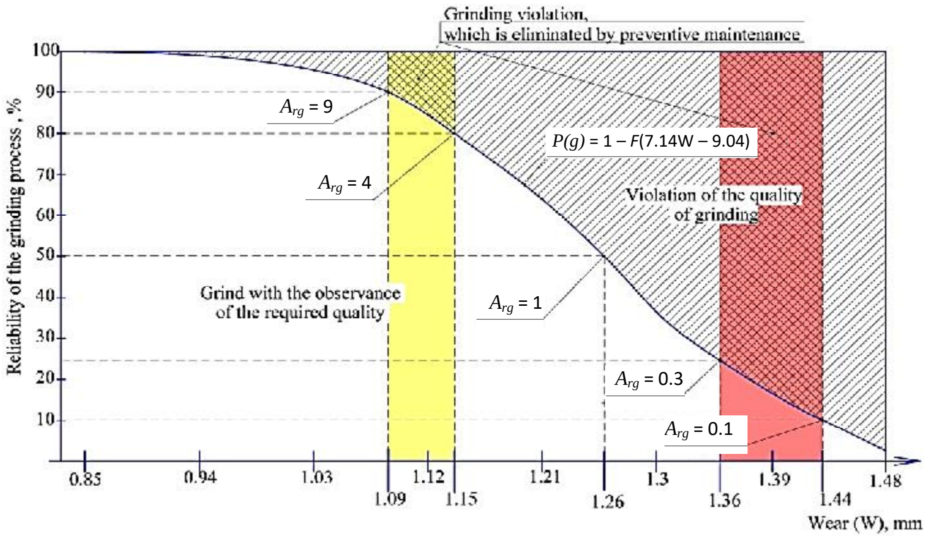

Figure 5. Dependence of reliability grinding process of grain materials wear riffles cutting element.

The obtained dependences are used to determine the amount of wear of the cutting edge (riffle) of the cutting element, which corresponds to the specified quality of grinding, according to the level of reliability of this process. So, for reliability $P(g)$ = 80–90%, the maximum allowable clearance should not exceed the range of 1.09–1.15 mm under these operating conditions.

The data obtained make it possible to build the dependences of ensuring the guaranteed grinding process on the tolerance for wear of the riffle of the cutting element, forming a gap between the working surfaces of the rotor and it. After an increase in the clearance value of more than 0.9 mm, periodically occurring failures in the loss of operation of the rotor crusher occur, consisting in a deviation of the norm of grinding of agricultural crops and the passage of full size grains. When changing the reliability of the grinding process by 10%, which corresponds to a change in the gap by 0.19 mm, out of 10 threshed tons of agricultural products, 1 ton does not meet the specified grinding requirements.

Therefore, to perform grain grinding with a process reliability of 90%, excluding disturbances in the operation of the rotary crusher, it is recommended to timely control the gap between the cutting element and the rotor at the level of 1.09 mm.

Techno-economic assessment of increasing resource rotor crusher with reference to four embodiments considered producing cutting element, for which made experiments with the grain of wheat s varieties ‘Yuka’, having microtrauma of seeds 27% and the content of mineral impurities 0.4%. Experiments were carried out at other equal conditions (the drive power of the electric motor of 1.5 kW, the length of the working part l = 0.06 m, the diameter of the rotor 0.1 m, circumferential speed of the rotor $v = 5$ m s^{-1}) and design parameters, which provided to productivity 0.3 ton h^{-1} (Table 1).

Table 1. The results of the evaluation of the technical and economic efficiency of the proposed options for rotary crushers

Indicators	Units	Options			
		1	2	3	4
S_w	ton	40.4	46.8	77.2	171.2
$S_{w80\%}$	ton	29.6	34	56.8	140
$S_{w\Delta 80\%}$	ton	10.8	12.8	20.4	31.2
$S_{w50\%}$	ton	34	39.2	65	152.8
$S_{w\Delta 50\%}$	ton	6.4	7.6	12.2	18.4
Time of work	hour	134	156	257	570
C_m	rubles	6,500	6,800	9,000	15,000
C_e	rubles	480	559	921	2,042
C_l	rubles	16,750	19,500	32,125	71,250
C_{pw}	rubles	300	1,000	1,400	1,950
C_t	rubles	24,030	2,7859	43,446	90,242
E_g	rubles ton^{-1}	594	595	562	527
$C_{\Delta 80\%}$	rubles	6,423	7619	11,480	16,445
$E_{g80\%}$	rubles ton^{-1}	1,405	1,414	1,326	1,171
$C_{\Delta 50\%}$	rubles	3,801	4,522	6,856	9,696
$E_{g50\%}$	rubles ton^{-1}	1,299	1,305	1,229	1,116

The calculation results in accordance with formulas (4) and (5) show that, without taking into account the quality (full wear) for the coated cutting element (option No. 4), the productivity and the criterion of technical and economic efficiency E_g respectively reach 171.2 tons and 527 rubles ton^{-1}, which indicates a greater wear resistance by 4.2 times compared with steel St3 (option No. 1) and an 11% decrease in technical and economic criteria.

When taking into account the quality of grinding, the volume corresponding to a given level of reliability will become less, but the additional volume $S_{w\Delta}$ will increase, requiring repeated processing, at least once. In this case, additional costs C_{Δ} are also required, which takes into account the technical and economic criterion E_g.

When the process reliability is 50% and 80%, the productivity is reduced, respectively, by 18.1–12.2% and 36.5–22.3% for all options, and the technical and economic criterion rises on average by 2.16 and 2.28 times.

These data allow us to confirm the hypothesis of the legitimacy of using all the proposed options for various forms of ownership of agricultural enterprises. For example, the crusher's maximum resource in the first and second manufacturing options, from the point of view of reducing their economic costs, can be recommended for private farms and peasant farms, in which the volume of processing and consumption of animal feed is from 30 to 35 tons per year. With an average cost of work equal to 1,410 rubles per ton of grinding. Also in favor of less durable structural materials is the simplicity of their machining, which makes it possible to carry out operations to restore working capacity in place without the use of spare parts.

The calculations are given in the currency of the Russian Federation (rubles), taking into account the cost of structural materials and technological operations to improve their characteristics according to data for December 2019.

CONCLUSIONS

– With the wear of the working bodies of the crusher, the degree of grinding of the source material, and hence the quality of the finished product, will also change. Grinding in compliance with the required quality is characterized by 100% process reliability, but during operation of the grinder, the probability of failure increases. According to an additional analysis should be carried out prevention when the culling wear of cutting element suitable the process reliability 80–90%.

– Analysis of the experimental results allows us to formulate several recommendations for grinding wheat on a horizontal rotary crusher:

1) for reliability *P(g)* = 80–90%, the maximum allowable clearance should not exceed the range of 1.09–1.15 mm under these operating conditions;

2) an increase in the gap value of more than 0.9 mm leads to periodically occurring failures and loss of operability of the rotor crusher;

3) given the reliability of the grinding process at 90% and to avoid disruption in the operation of the rotary crusher, it is recommended to replace or adjust the cutting element with a gap of 1.09 mm.

– Comparative evaluation of shredders recommend performed using technical-economic indicator E_g. This is due to the appearance of additional costs C_Δ in the form of carrying out an additional amount of work $S_{w\Delta}$ related to bringing the substandard product to a given particle size distribution. Based on this, two types of the process can be distinguished:

1) at the maximum wear (the reliability 10–25%) of the cutting element according to option No. 4, the productivity amounted to 171.2 tons of crushed grain, and the efficiency criterion was 527 rubles/ton, which is 4.2 times higher compared to according option No. 1 on productivity, and by 11% lower by technical and economic criteria;

2) taking into account the reliability of the process, 50% and 80%, the operating time is reduced, respectively, by 18.1–12.2% and by 36.5–22.3% for all options, and the technical and economic criterion rises on average by 2.16 and 2.28 times.

– The cost of manufacturing more expensive, but wear-resistant cutting surfaces will not always be the best option, for example, inexpensive and less durable options No. 1 and No. 2 can be recommended for small forms of ownership, the productivity of which is up to 35 tons per year.

ACKNOWLEDGEMENTS. The authors would like to acknowledge rector of FSBEI HE ‘Stavropol State Agrarian University’ V ruhachev and the chairman of agricultural production cooperative ‘Kazminsky’ in the Stavropol Territory of Russian Federation S. Shumsky for comprehensive support in conducting research work.

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