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Refinement of the engineering practice of evaluation of the wear rate of excavator implement components

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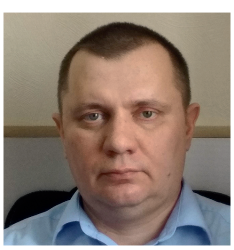

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Abstract. *The existence of humankind on Earth largely depends on the energy at its disposal. It is mostly generated by processing minerals extracted from the Earth's crust by open-cut mining. The quality and low cost of extraction are largely defined by the dependability of employed machines and mechanisms, plants and process engineering solutions. Various types of excavators are the backbone of a mining machine fleet. Their parts that principally interact with the environment (rock) are components of implements, i.e. primarily the buckets and components of bucket(s). It must be noted that in the process of interaction with the environment (rock) the excavator implements and their components are exposed to so-called abrasive wear. Since abrasive wear of implement components (most frequently excavator bucket teeth) causes their recurrent replacement, this inevitably affects the performance of the excavator as a whole and those process flows it is part of. Occasional interruptions of operation and repairs reduce the availability factor, the most important complex indicator of equipment dependability. Given the above, the aim of this paper is to refine the previously known formula proposed more than thirty years ago in VNIISDM (Reysh A.K.) for evaluation of the rate of abrasive wear of excavator bucket teeth. For the first time, with a sufficient accuracy we examined the multitude of operating modes of mining equipment, i.e. operation of excavators in various conditions, e.g. on different soils. Additionally, we extended Reysh's approach from single-bucket machines to continuous operation multi-bucket ones. For that purpose, the authors used a method of data integration from known sources, method of full-scale experiment under the operating conditions of a specific excavator and method of mathematical simulation (a form of the Monte Carlo method). All of that allowed revising the values of the parameters in the Reysh formula. The refined formula that we obtained can now be used for the dependability evaluation of machines operating under varying conditions, as well as for the purpose of appointing the time of preventive inspections.*

Keywords: *wear, wear rate, bucket wheel excavator, bucket teeth, mine rock, operating modes.*

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Relevance and state of the art. Stable development of Russia's fuel and energy industry directly depends on the reliable and productive operation of the existing manufacturing chains, starting from single mining machines to plants and ultimately high technology power station equipment. The primary task of open pit mining was and is to ensure convenient, complete and cost-efficient access to mineral resources. For that purpose, various machines, plants and processes are used.

For the sake of specificity, this paper considers the SRs(k)-4000 continuous operation bucket wheel excavator (Germany) in operation for many years in Krasnoyarsk Krai (Nazarovskoe brown coal field).

Figure 1 shows the graph of the expected C_{TA} availability coefficients of the above equipment. It is evident that the actual dependability indicator does not reach the expected value, which indicates the requirement to develop and implement measures to as quickly as possible correct this negative situation.

It is known that the availability of machines for use in time is largely ensured by reliable operation of all units and mechanisms [1 – 5 and many others]. Failure analysis shows that most idle hours of any excavator (including the one under consideration) are associated with the recovery of the implements, more specifically the replacement of worn-out bucket teeth. That is confirmed by Fig. 2. The main factor causing failures of bucket teeth (Fig. 3) and their components is abrasive wear (Fig. 4).

Abrasive wear is the subject of many research papers (a sufficiently good pre-1980 study can be found, for example, in [6]).

The works of Khrushchiov M.M. [7 and many others], Kragelsky I.V. [8 and many others], Drozdov Yu.N. [9 and many others] and Kostetsky B.I. [10 and many others] are now considered among the most fundamental studies of abrasive wear.

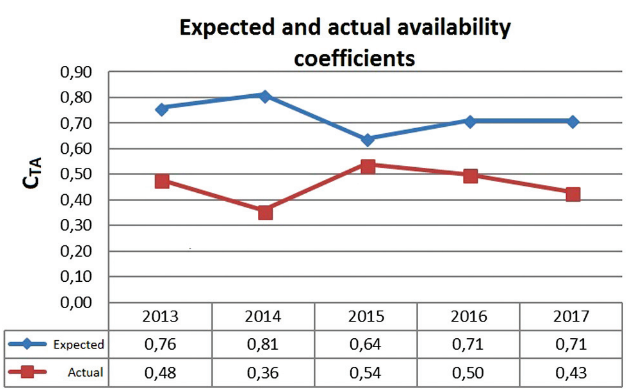

Figure 1. Expected and actual availability coefficients of the SRs(k)-4000 excavator

Figure 3. Bucket of a bucket wheel excavator

As regards mining and construction vehicles, the following well-known experts were involved with this subject

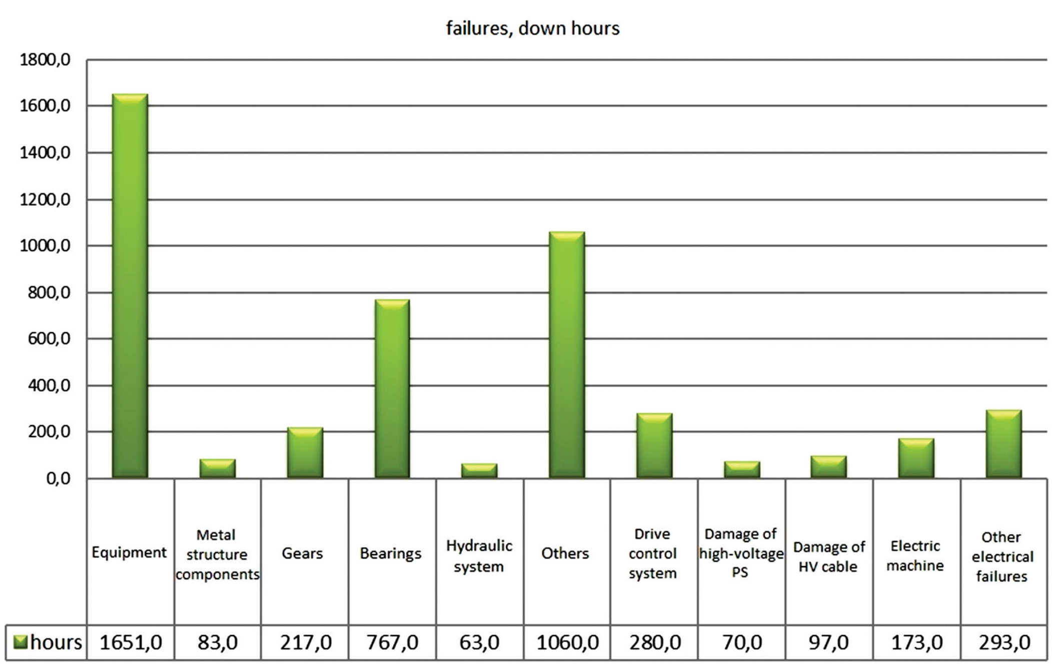

Figure 2. Diagram of failure distribution of excavator components in 2013 – 2017

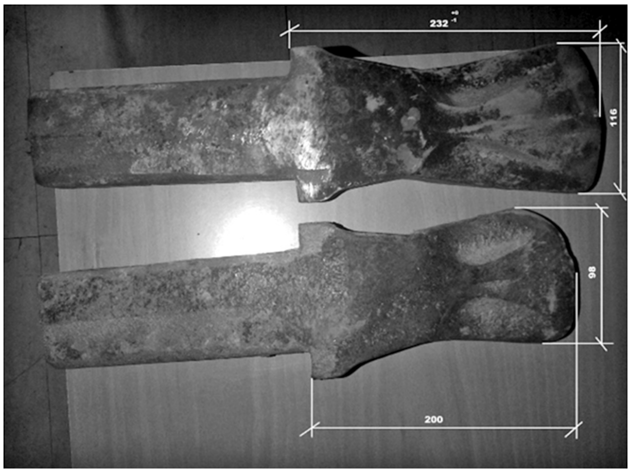

Figure 4. SRs excavator tooth before (above) and after (below) use

matter in its various aspects and in different time periods: Abezgauz V.D. [11 and others], Akilev S.A., Banatov P.S., Baron L.I., Bogolyubov B.N. [12 and others], Valova L.S., Vetrov Yu.A. [13 and others], Vinogradov V.N., Glatman L.B., Goryushkin N.N., Grinberg N.A., Dombrovskaya I.K., Evdokimov Yu.A., Zimin A.I. [14 and others], Zorin V.A., Ikramov U. [6, 15 and others], Kabashev R.A., Kovalchuk V.A., Kolesov V.G., Kokh P.I., Larionov V.P., Leshchiner V.B., Lifshits L.S., Lvov P.N., Metlin Yu.K., Novikov I.V., Papić L. [16 and others], Petrov I.V., Pristaylo Yu.P., Reysh A.K. [17 and others], Smorodinov M.I., Solod G.I., Sorokin G.M., Tenenbaum M.M. [18 and others], Tkachiov V.N. [19 and others], Toropov V.A., Faddeev B.V., Frolov P.T., Kharach G.M., Chudakov K.P., Shreyner L.A., Yampolsky G.Ya. [20] and many others.

However, despite extensive research conducted in the area of abrasive wear, many practically important problems are yet to be resolved.

Thus, still unsolved is the problem of evaluation of wear rate of excavator implement components, i.e. bucket teeth and their components [see for example, 17, 21 – 26 and many others].

In [17], written over thirty years ago, its author proposes an empirical formula to estimate the wear rate of excavator teeth. However, due to the large number of empirical coefficients whose values were not known to the author, it was impossible to be used (out of all practically interesting approaches that we know of this one appears to be the most advantageous).

This paper is dedicated to changing this negative situation.

Theoretical foundations. On the refinement of the Reysh formula [17]. In [17], the author proposed a formula for estimation of a bucket tooth service life as follows:

$$t_{\text{H}} = \frac{U_D}{\gamma}, \tag{1}$$

where U_D is the allowed wear of the tooth (for the purpose of engineering calculations it is normally recommended to take this parameter as half or its working length); γ is the wear rate that was proposed to be estimated using an empirical formula as follows:

$$\gamma = (A \cdot P \cdot C_{p0} \cdot C_{vp0} \cdot f \cdot s \cdot t_{\text{D}} \cdot C_{\text{y}} \cdot C_{\text{ABR}} \cdot \frac{1}{C_{\text{WEAR}}}) \cdot C_{t20}, \tag{2}$$

where A is the proportionality factor; P is the pressure on the tooth's working surface; C_{p0} is the coefficient that takes into account the effect of changing pressure; C_{vp0} is the coefficient that takes into account the effect of the frequency of pressure change; f is friction coefficient; s is the tooth's rubbing path; t_D is the duration of digging; C_U is the coefficient that takes into account tooth dulling; C_{ABR} is the soil abrasion factor; C_{WEAR} is wear resistance coefficient; C_{t20} is the coefficient that takes into account the ambient temperature.

As formula (2) shows, its successful application requires a significant amount of experimental data. A part of this data is known with sufficient accuracy for engineering calculations ($P, f, s, t_{\text{D}}, C_{\text{U}}, C_{\text{ABR}}, C_{\text{WEAR}}, C_{t20}$) [2, 6-19, 22-26 and many others], for some parameters only the possible ranges of values are known (C_{p0}, C_{vp0}), while for parameter A no data is known as of today (that the author of [17] openly states).

Thus, understandably common engineers cannot use formula (2) (let us note that the author of this formula also allowed an unfortunate inaccuracy in the dimensionality). A research is to be done in order to identify the values coefficient A can take (to at least understand the order of magnitude).

For that purpose, we propose to rewrite formula (2) in a more convenient, in our opinion, form:

$$\gamma = A \cdot C_1 \cdot C_2 = A \cdot \prod_{j=1}^{m} C_j \cdot \prod_{i=1}^{k} C_i, \tag{3}$$

where $C_1 = \prod_{j=1}^{m} C_j$ is the first generalized wear coefficient not depending on the machine's operating mode that, obviously, equals to the product of a number of coefficients (f, C_{ABR}, C_{WEAR} and C_{t20}); $C_2 = \prod_{i=1}^{k} C_i$ is the second generalized wear coefficient that depends the machine's operating mode that also obviously equals to the product of a number of other coefficients (P, C_{p0}, C_{vp0}, s, t_{D}, C_{U}).

This new notation allows, if necessary, considering individually the behavior of groups of empirical coefficients and more accurately take into account the operational specifics of the individual excavators.

Let us note that for the above-mentioned excavator we know both the range of values of teeth wear and the extreme values of the coefficients of equation (2) for specific operating conditions.

Then, using the previously conducted experimental research, we will estimate the possible values of coefficient A in accordance with the obvious formula:

$$A = \frac{\gamma}{C_1 \cdot C_2}. \tag{4}$$

Table 1. Coefficients among the second generalized wear coefficient

C_p0	$C_{vp}0$	*s*, m	t_D, s	C_U*	*P*, MPA
1	2	3	4	5	6
0.6 – 3	0.6 – 1.54	5 – 10	3600	1.088 – 1.132	0.1 – 2.0

* this parameter is identified using formula [17]: C_U=1+0,44·U, where *U* is the projection of wear surface (normally from 0.2 to 0.3 m).

Table 2. Coefficients among the first generalized wear coefficient

f	C_{ABR}	C_{WEAR}	C_t20
1	2	3	4
0.25 – 0.8	0.7 – 6.6	1.0 – 2.1	C_{t20}=(0.05…0.08) ·t_F*

* the t_F parameter is the actual temperature within the range from -60 to +50 degrees Celsius (in our opinion it must be modulo, excluding the value equal to zero).

Table 3. Distribution of excavator operation time per type of soil and some of their characteristics

Type of soil	Average portion of operation time, p_i	Specific weight of soil, ρ, t/m³	Friction coefficient, *f*	Ground abrasion factor, C_{ABR}
1	2	3	4	5
Peat	0.15	0.8 … 1.2*	0.25	0.7
Loams	0.25	2.04	0.30	1.66
Silt	0.1	1.8 … 2.0*	0.25	1.0
Aleurolites	0.1	2.04 … 2.15	0.50	1.0
Clay	0.15	2.03	0.35	1.2
Argillaceous sandstone	0.25	2.4	0.30	6.6
	Σp_i=1,0**			

* the precise value significantly depends on the humidity.

Tables 1 and 2 show the initial data for calculation.

Accounting for operation in different modes. Some of the above coefficients depend on the type of soil. In order to more accurately take account for this factor subject to a specific excavator's operating conditions based on its operational dependability data we created the so-called generalized series that takes into consideration the multi-mode nature of the product's operation. That is due to the fact that during the period of operation in question the SRs(k)-4000 bucket wheel excavator worked on various soils.

Table 3 contains a number of characteristics of the operating conditions of the excavator in question that are required for the creation of the above generalized series. We made it based on the expert estimations and analysis of known literature.

Let us note that data per the coefficients were collected for each of the modes.

Further, for each *i*-th mode, using formula (3) individual wear rate γ^i was identified taking into account the data from the tables. Since wear-related degradation damage accumulates all operating modes, applying the above formulas requires estimating the average wear rate $\bar{\gamma}$ taking into account the generalized series information from the tables.

The average rate $\bar{\gamma}$ is expressed as the quotient of the total distance by the total time, while the distance U_Σ is the amount of total wear, mm:

$$\bar{\gamma} = \frac{U_\Sigma}{T} = \frac{1}{T}\sum_{i=1}^{k}\gamma^i \cdot T \cdot p_i = \sum_{i=1}^{k}\gamma^i \cdot p_i, \qquad (5)$$

where *T* is the total operation time; *k* is the number of operating modes under consideration.

Let us note that while deriving formula (5) we used obvious formulas of the form $t_i=T{\cdot}p_i$, where t_i is the operation time in the *i*-th mode and $U_\Sigma = \sum_{i=1}^{k} U_i = \sum_{i=1}^{k}\gamma^i t_i$.

Thus, it can be stated that the average wear rate under time-specific apportionment of operating modes is the arithmetical value of the modes subject to portions p_i.

Regarding coefficient *A*. Under the time *T*, h, known from the full-scale experiment the possible numerical values of the proportionality coefficient *A* are identified based on the above formulas and tables.

Our average estimate of the coefficient was: $A = 8.1{\cdot}10^{-8}$ 1/(PA·h) provided that γ has the dimensionality of m/h.

Nevertheless, as the dependability theory goes [27, 28 and many others] point estimation alone does not suffice. In order to estimate the confidence intervals per parameter *A*, assuming that all the required parameters (some of which, let us remember, are within the above ranges) that, obviously, generally are stochastic, have normal distribution with average values corresponding with the middles of the intervals and given variation coefficients, let us use the Monte Carlo method [29 and many others] (an example is given in [30]).

As the result, in calculating the distribution of constant *A* with 90% variation for several variables the confidence interval for *A* under the assumption of normal distribution of the values from the above tables according to preliminary calculations is $6{,}8\cdot10^{-8}\dots 1{,}2\cdot10^{-8}$.

The calculations were performed in the R programming environment [35]. An example of application is in [36].

Conclusion. Based on both the experimental data we obtained regarding the operation of a bucket wheel excavator under various operating conditions over a long period of time and taking into account out analysis of the available literature we estimated the coefficient in the formula used for calculation of the wear rate.

At the same time, we evaluated the accuracy of the results.

In conclusion, we can state that now the Reysh formula can be successfully used in the assignment of inspections, repairs and replacements, as well as for the analysis of the effect of the operational factors (optimization goals can be set in a way similar to that described in [31], in particular, taking into account the economic criteria).

Additionally, now we can set and subsequently successfully solve the problem of spare parts and tools optimization in respect to mining excavators and in individual repair units, for example in the way proposed in [32].

Obviously, the applicability of the Reysh formula is a significant contribution to the design of the method of prediction, maintenance and, as far as possible, improvement of the dependability of quarry mining machines ([33] can be cited as an example).

In conclusion let us note that although the study was conducted on a specific excavator operated under specific conditions, the generality of the findings will not be lost as the conditions of the Nazarovsky mine and Krasnoyarsk Krai as a whole are quite typical in terms of such machines' operation in Russia. The conditions of Ukraine or Kazakhstan and other regions will possibly require the data presented in this paper to be refined.

We will continue the respective activities both in terms of further refinement of the values of coefficient *A* and examination of other types of excavators. The methods of collection and processing of expert information will also be essentially improved (based, for example, on [34 and many others]).

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