On the prospects of research in the field of evaluation and reduction of mining machines elements wear

P A Pobegailo¹, I V Gadolina¹ and Ju A Gustov²

¹ Mechanical Engineering Research Institute of the Russian Academy of Sciences (IMASH RAN), Moscow, Russia
² Moscow State University of Civil Engineering (MGSU) National Research University, Moscow, Russia

gadolina@mail.ru

Abstract. In this paper, the authors present some considerations on how to develop studies of wear (wear resistance) of mining machines for open-pit mining. First, the need to continue research aimed at adapting the A.K. Reisch's approach was noted to clarify and improve the empirical formula to assess the wear rate of elements of mining and road machines. Secondly, it is planned to deepen research to assess the correlations between the properties of materials used in mining engineering and characteristics of their wear resistance. Thirdly, the problem of wear of elements of mining machines is considered from the standpoint of managing the phenomenon of wear. For this, the A.K. Reisch's empirical formula can be used, and the optimization problem formulated in a general form, which is reduced to maximizing the productivity of the machine with restrictions on the rate of wear of its elements and the operating costs. Fourth, the relationship between the problem of managing the phenomenon of wear and the dynamics of mining machines is noted. Some of these researches are illustrated by examples of a qualitative nature.

1. Introduction

As long as humanity does not master thermonuclear energy sources, it is doomed to use traditional minerals. Minerals are extracted from the ground in both open-pit and underground mining operations. It is obvious that now all the main stages of mining are mechanized. Machines, which involved in mining, are characterized by complexity, size, weight and high cost. The operation of these machines often takes place in the most difficult climatic and mining conditions. Management of these machines is most often carried out by a person, with all the resulting pros and cons.

One of the main problems that stand in the way of effective use of the entire class of mining machines is the presence of friction forces, which, in particular, cause the phenomenon of wear of elements and connecting parts of mining machines.

Mining operations and equipment for them have been known to people for more than one century. And all this time, people are trying to reduce the effect of friction and wear. Basically, it has always been dedicated to finding new design solutions for machines, technological methods of their application, and the use of new materials. In the last 50 - 60 years, theoretical scientific research has also appeared, often with a capital experimental base. These studies are aimed at establishing the features of the process of friction and wear in the machines themselves, followed by generalization of
private research in the structure of the General theory. Unfortunately, it was not possible to create a unified General theory of friction and wear of elements of mining machines. At the same time, due to the well-known events of the 90s of the last century, most of the experimental materials were lost in our country.

Known from the numerous literature approaches to the assessment of friction and wear in mining engineering mostly are reduced to the technique for underground mining. There are significantly fewer studies of open-pit machines. There are no experimental or theoretically based formulas in the published works.

Also, we are not aware of the work aimed at controlling the processes of friction and wear of mining machines. Let's try to talk about this on the example of mining excavators and the recommended for them in our works (e.g. in [1]) empirical formula of Reish A. K. [2] for estimation of wear rate of teeth and the cutting edge of the bucket teeth of rotary wheel.

2. Formula for wear rate estimation

Now we recall the General form of the Reish A. K. formula [1, 2]:

$$\gamma = (A \cdot P \cdot K_{p0} \cdot K_{vp0} \cdot f \cdot s \cdot t_p \cdot K_U \cdot K_{ABR} \cdot \frac{1}{K_{IZN}}) \cdot K_{120}$$

(1)

where $A$ is the proportionality coefficient; $P$ is the pressure on the working surface of the tooth; $K_{p0}$ is the coefficient taking into account the influence of pressure changes; $K_{vp0}$ is the coefficient taking into account the influence of frequency of pressure change; $f$ is the friction coefficient; $s$ is the path of friction of the tooth; $t_p$ – the duration of the digging; $K_U$ is the coefficient taking into account the blunting of the tooth; $K_{ABR}$ is the coefficient of the abrasiveness of the soil; $K_{IZN}$ is the coefficient of wear resistance; $K_{120}$ is the coefficient taking into account ambient temperature.

This formula is purely empirical. Its author proposed it in the last century for a wide class of construction and road vehicles, based on his research over a period of more than thirty years (mainly in VNIISDM institution). However, the values of many coefficients of this formula are determined by him inaccurately enough, and when describing the coefficient $A$, an error was made in determining its dimension. It was also not explained how this coefficient can be determined. For this reason, the formula (1) in the form presented in the monograph [2] cannot be used in the practice of designing and operating any machines. It needs to be carefully refined to transferring this formula to other types and types of machines, for example, to machines for open-pit mining excavators.

The form of formula (1) shows that it is linear in the sense that changing the initial data will change the result proportionally. However, in reality, mining machines are essentially nonlinear systems.

There is a certain kind of dialectical contradiction – a simple linear formula with which the engineer can work and a real expressed nonlinear system. Within the framework of engineering methodology, you can close your eyes to this, but it should be noted that some of the empirical coefficients in formula (1) change non-linearly. Therefore, their definition is problematic. The coefficients in formula (1) can be divided into a number of groups based on certain criteria.

Thus, we can distinguish linear and nonlinear terms. This is useful when setting up theoretical research in research institutions. In engineering practice, it is more useful to divide these coefficients into groups based on the ease of determining them and their contribution to the assessment of the wear rate.

For example, it might look like this-the coefficients $s$, $t_p$, depend on the operation of a particular machine (its operator) and on what technological scheme the unit participates in.

The coefficients $K_{120}$, $f$, $K_U$, $K_{ABR}$ and $K_{IZN}$ depend mainly on external conditions.
The coefficients $P$, $K_{p0}$, $K_{vp0}$ depend on how the process of interaction of the working body with the wear medium proceeds.

The last group of coefficients are "Terra Incognita" for modern science. Some works in this area are contradictory and not very informative [3-5, etc.]. You have to choose which of the previous authors can be trusted and rely on their ideas. In fact, this is a large and important area for future fundamental research.

A special place is occupied by the proportionality coefficient $A$. It is precisely its precise selection that can allow us to control the wear rate at the first stage of our research. However, its determination is still possible only for specific mining and geological and temperature conditions when analyzing the operation of a specific machine. In the process of accumulating our knowledge about the wear process of specific types of mining machines in typical operating conditions, we should strive to exclude this coefficient from formula (1).

It is important to note that a number of empirical coefficients significantly depend on the quality and properties of materials, as well as metallurgical technologies for their manufacture. Thus, different properties of steel, that have some acceptable variation in the manufacture of a machine at the factory, can greatly affect the performance of the same machine, made at different times, from different batches of steel, but for the same working project.

This requires setting and considering the problem of analyzing the influence of the spread of material properties. In addition, it is of great importance to study the influence of impurities added to steel by searching for linear regression coefficients.

3. Analysis of factors interaction

As an example, we note that it is important to obtain empirical dependencies for the refinement of the wear rate constants. In [6, 7], it is stated that "hardness will be an integral component in the criterion for evaluating the wear resistance of steel during mechanical wear". An ambiguous effect of strength was also noted. Reliable confirmation of this information is complicated by the problem of setting up a laboratory experiment with varying factors, since they are often mutually dependent. Based on the materials of [6, 7, etc.] figure 1 shows some of the graphical pair correlations of the factors.

![Figure 1. Pair correlations of the factors.](image)
The graph shown in Figure 1 shows paired correlations of factors for a sample of 55 elements borrowed from table in [6, 7]. Notation: temper - temperature of steels, °C; HRC - hardness, HRC\(^{-1}\); inverse value of hardness, HRC\(^{-1}\); Sig\(\text{V}\) - tensile strength of steel samples, MPa, wear - wear rate; lg\(\text{wear}\) - logarithm of the wear rate. The graph is built in the R programming environment [8].

The transformations for the values of hardness and wear rate were an attempt to linearize the bonds. However, there are no obvious correlations for any pair. The tempering temperature factor was excluded from further analysis.

Next, a linear multiple regression analysis was performed, in which the wear rate was used as the response. Based on the data from [6, 7, etc.], abbreviated due to the lack of exhaustive information in some experiments, equation (2) was obtained:

\[
\text{Wear} = 0.37 + 0.044 \text{HRC} - 0.00085 \text{SigV}
\]

The analysis, without claiming to be deeply scientific, demonstrates the approximate nature of the dependence of the wear rate on the most significant factors. The obtained dependence can later be used in planning an experiment to analyze the influence of technological factors on the quality of products according to the wear rate criterion.

An example of successful application of experiment planning using the Taguchi method in the problem of optimizing the mechanical and tribological properties of composites is given in [9]. The authors managed to optimize the homogeneity of the mixture in a 3D printer by specifically varying three parameters: the speed of the extruder screw, the temperature of the layer application, and the layer volume.

4. Optimization
The controlling the wear rate of mining machine elements is closely related to their performance (\(P\)). Thus, by increasing the speed of movement of the working body, we usually increase the wear rate, but we win in productivity. However, operating costs increase (\(\Delta Z\)). Obviously, there is a need to find some compromise.

Now we write the optimization problem in the form, which is possible at present:

\[
P \to \text{MAX} \\
\text{MIN} \leq \gamma \leq \text{MAX} \\
\Delta Z \leq \text{MAX}
\]

Here we assume that the performance of the excavator should be maximum with restrictions on extreme wear limits (since the range of speed control of the rotary wheel is limited) and on maximum operating costs.

Note that at present it may be necessary to provide not the maximum performance of the machine, but the desired one within its possible extreme limits. However, this does not prevent us from using the formulation (3), since, in fact, only the value of the optimization parameter MAX changes.

Note that statement (3) makes sense for organizations that operate the machine; in the design office, there problem can be written more accurately and at a higher scientific level – for example, a complex and nonlinear function of operating costs requires a separate in-depth study. The same applies to the drive of an individual car: if in the design office it can be changed in a wide range, in practice this is impossible.

Due to this reason, the problem of wear rate management is closely connected with the analysis and optimization of the drive of machines. So, for the excavator – dragline winch moving equation was obtained:

\[
J\ddot{\varphi} = M_a - \frac{\lambda}{\omega - \varphi} - R \cdot (P_a + R \cdot \varphi \cdot (P_b + E \cdot F)) - R
\]

Here: \(J\) is the moment of inertia brought to the shaft of the winch drum;
\( \ddot{\phi} \) is the second time derivative of the angular movement of the drum;  
\( R \) is the diameter of the drum on the rope winding layer;  
\( P_0 \) is the minimum total force in the traction ropes, at the beginning of its movement;  
\( E \) is elastic modulus of the rope;  
\( F \) is the cross-sectional area of the rope (total for two branches);  
\( \phi \) is the value of the angular movement of the drum;  
\( \dot{\phi} \) is the first time derivative of the angular movement of the drum;  
\( R \) is a complex function that describes the behavior of the value of the digging resistance force on the bucket teeth;  
\( M_0, \omega \) and \( \lambda \) are some parameters of the mechanical characteristic.

This equation shows the nature of a complex relationship between the forces of soil resistance to digging applied to the bucket teeth and the parameters of the traction winch drive. By changing the latter, we can influence the wear of the teeth, since it is closely related to the efforts of soil resistance to digging.

5. Conclusions

This paper identifies some possible and important areas for further research on mining machine wear, namely:

- for the first time in our country, the problem of friction and wear control has been formulated for mining machines;
- coefficients are specified in the formula of A. K. Reish, which can serve as a basis for managing wear in the practice of operating mining machines;
- the task of optimizing the performance of a mining machine with restrictions on the permissible operating costs and the wear rate of elements of mining machines is set;
- given the close relationship between the wear and the dynamics of the actuator;
- based on reference data, the influence of operational factors on the wear rate is analyzed;
- the problem of accounting for and influence of stochastic properties of materials used in mining engineering and the impact of this on wear is outlined.

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