High temperature wear assessment of mining machines operating tools

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Abstract. Mining is widely associated with the use of a variety of mining machines for various duties, such as extraction, loading and transportation of rock. Due to prolonged use of machines, the amount of wear of operating tools and machine parts increases. This problem is especially acute for mining and loading machines used in excavation and reclamation, because the wear rate is increased on those duties. The development of wear process and evaluation of the residual life of operating tools of mining and loading machines is well studied in world practice. However, given the variety of climatic, geological and mining conditions, unique for each mineral deposit, we are facing difficulties in creating a comprehensive model of wear process development. In modern researches on this area such issues as estimation of operating tools residual life during intense wear under extreme conditions of high temperatures and sharp temperature drop are understudied. These conditions are typical for deposits of such minerals as coal and peat, which are especially prone to spontaneous combustion. This review discusses methods for assessing various wear mechanisms and the effect of temperature on the intensity of those processes, as well as methods to determine the residual life of operating tools of mining and loading machines working in high-temperature environment.

1 Introduction

The operating tools of mining and loading mining machines are subjected to significant stresses during numerous loading cycles, which leads to failure of tools. Some authors [1, 2] classify forms of failure into wear and destruction. In practice, these processes are difficult to distinguish from each other.

Wear is defined as the process of separation of material from the surface of a solid material, as well as an increase in its residual deformation, which manifests itself in a change in shape [1]. Wearing of the surfaces of parts, tools, and mechanisms occurs when physical and mechanical processes, mainly friction, are activated in the surface layer over a certain area, and the consequence of those processes is separation, peeling, or deformation of the material in the exposed area.

There are several mechanisms of the wear process. As noted in [1, 3], most authors distinguish a group of mechanical types of wear, such as abrasive wear, mechanical fatigue, separation of material by chipping, and also a group that includes diffusion and adhesion, as well as such types of wear, as thermal fatigue, oxidation, etc.

The abrasive wear arises as a result of friction of solid rough surfaces with the formation of scratches and peeling of the material. According to the statistical analysis presented in [3], abrasive wear is the main cause of failure of drilling tools. The tooth may lose up to 13-17% of the initial mass during prolonged wear over the period of 100-150 machine-hours [4].

Although the mechanism of abrasive wear is not temperature depending, an increase in temperature leads to a decrease in hardness of most types of steel, thereby reducing the amount of applied load necessary for the appearance of defects [5-8].

Abrasive and adhesive wear of rock-cutting and loading tools is characteristic under low-temperature conditions at low cutting speed, diffusion wear and oxidation processes are activated at high temperatures, which ultimately accelerates the wear rate (Fig. 1).

At the first stage of adhesive interaction, contact between the abrasive and the abrasion surface becomes possible due to the appearance of high contact pressure, which causes local plastic deformation. Then, as a result of the movement of the abrasive and the wearing material, the "seizure bridges" in the contact zone of the two surfaces are destroyed. The intensity of development of these processes depends on the difference in hardness between the workpiece and the abrasive material, as well as on the difference in heat resistance of materials [3].

The intensity of diffusion wear depends primarily on the chemical composition of the contacting surfaces [6]. In a high cycle load, fatigue wear occurs [9], and in the zone of elevated temperatures and due to large number of metal heating-cooling cycles, thermal fatigue occurs. As a result of those processes, elastic deformation of the metal crystal lattice, dislocation, and other defects arise, which lead to the formation of microcracks. With the accumulation and growth of microcracks, the material breaks off and delaminates, which leads to a decrease in the productivity of mining machines cutting tools. [2, 5]

Fig. 1. Relationship between life time of operating tool and contact surface temperature [1].

High-temperature conditions during coal and peat mining and reclamation occur due to spontaneous combustion and endogenous fires of rock mass [10]. Such conditions significantly accelerate wear processes and reduce the lifespan, so it is important to develop a method to assess the rate of high-temperature wear, that takes into account the effect of all wear mechanisms.

2 Materials and methods

To predict the lifespan of cutting edges of mining machines, such as bucket teeth, it is necessary to assess the residual resource of operating tools. Many authors draw on the

practical approach to determine the residual resource, which doesn't include the assessment of all wear mechanisms.

To study the wear rate of specific operating tools, many authors resort to the method of theoretical and mathematical modeling, including an assessment of the mechanical characteristics and chemical composition of steel. The construction of von Mises stress fields (Fig. 2) to determine the zones most susceptible to deformations can be found in [11, 12], the analysis of defects and fatigue characteristics using finite element method can be found in [13, 14]. The authors in [15] made the computer model of a moving bucket and studies the motion of a granular medium to find high pressure zones at the rear side of the bucket.

Fig. 2. Von Mises stress field of an excavator bucket (red spots indicate values over 355 MPa) [11].

Such methods are suitable for detecting internal defects, but do not take into account many factors and wear mechanisms.

Since the statistically most repetitive cause of failure is abrasion wear, most studies focus on assessing the intensity of abrasion. So, the author in [16] conducted an experiment to establish the relationship between the intensity of removal of the Stellite coating from the steel sheet and cutting parameters. A similar experiment was carried out in [17]. Both authors concluded that the main factor of abrasion wear and of increase of surface hardness is feed rate. Other factors of wear are abrasion at low cutting speeds (<30 m / min) and breaks, delamination and chipping at high speeds (> 30 m / min).

However, as noted in [1, 18] with an increase of contact temperature, high-temperature fatigue wear, diffusion and oxidation processes are emerge, although many of the existing tests of wear intensity at high contact temperatures do not take into account the complex of these mechanisms, most often resorting to the study of adhesion and high temperature abrasion wear.

Strictly speaking, the intensity of the wear process also increases with temperature. This is confirmed by many experimental studies in the field of materials science. Results of such experiments described in [19-21] are similar: with an increase of the contact temperature, the mass loss of all the tested steels also increases. However, some types of steels are able to form a tribological layer in an abrasive medium, which increases wear resistance, even at high temperatures (Fig. 3).

Resistance to high temperature wear is mainly affected by the phase composition and steel structure [18]. Steels with an austenitic microstructure can withstand a greater number of fatigue load cycles than steels in which the phase transformation to perlite occurred [18, 22].

The experiment described in [22] clearly shows that certain transformations occur during a multiple cycle of heat treatment and cooling. At a temperature of 500°C , as the author noted, the phase transformation of austenite to perlite occurs, reaching a maximum value of

24% after 36 cycles. Thus, during long-term fatigue loads, phase transformations of austenite to perlite occur in steel, which lead to occurrence of microcracks and peeling of the material.

Fig. 3. Different types of steel abrasive wear rate values for different temperatures [20]

Similar results can be found in other researches. As it described in [6], even a one cycle heating to 850 °C and cooling to the room temperature leads to a decrease of the fatigue strength. A similar result can be found in [23]; in this case, a multiple heating cycle to 950 °C was carried out. As a result, it was found that the number of microcracks increased.

In addition to the above methods, which are mostly based on experimental studies, the lifespan and residual resource of operating tools can also be determined by the calculation method. For example, in [24] a method to calculate the value of the intensity of adhesive-fatigue wear of cutting tools using the coefficient of thermal diffusion evaluation was proposed; in [25] a method for calculating the fatigue wear by calculating the internal heat dissipation and the development of microplasticity is presented, the calculation results have a good correlation with experimental data obtained by the same author; in [25] a method for quantitative calculation of the residual resource by the size of microcracks on a SEM images is presented.

As noted in [26], the prevailing wear mechanism may depend on the type of material of the cutting tools and the type of rock. The authors in [1, 26] presented a number of functions to determine the volume of wear products for a specific wear mechanism (Table 1).

Table 1. Formulae to determine volume of wear product for different wear mechanism [26].

Wear mechanism	Formula to determine the volume of wear product, m ³	Explanations
Abrasive	$K_{abr}K\left(\frac{P_a^{n-1}}{P_t^n}\right)V_cwVB\bar{\sigma}\Delta t$	K_{abr} – abrasive wear coefficient, m ³ /N; P_a – abrasive particle hardness, MPa; P_t – tool hardness, MPa; n and K – coefficients; V_c – velocity of flank wear, m/s; VB – flank wear length, m; w – width of cut, m; $\bar{\sigma}$ – average normal stress, N; Δt – time interval, s
Adhesive	$K_{adh}e^{aT}V_cw\bar{\sigma}\Delta t$	K_{adh} – adhesive wear coefficient, m ³ /N; a – hardness constant; T – temperature, K
Diffusive	$K_{diff}\sqrt{V_cVB}e^{-\frac{K_Q}{T+273}}w\Delta t$	K_{diff} diffusive wear coefficient, m ³ /N; K_Q – constant, related with activation energy for diffusion

Oxidation	$K_{ox} \frac{W}{3\sigma T} V_c \Delta t$	K_{ox} – chemical wear coefficient, m ³ /N; W – applied load, N

3 Results and discussion

The main goal of the review was to find the ways to assess the intensity of the main factors and mechanisms that affect the process of wear of mining machines operating tools during excavation of high temperature rocks.

High temperatures increase the wear rate, one of the factors of this phenomenon is phase transformations in steel, which leads to a decrease in wear resistance [8, 18]. These processes are exacerbated by a multiple heating-cooling cycle. [7, 20, 22]

The dominant wear mechanisms at high temperatures are abrasive and adhesive wear, as well as thermal fatigue [1, 26].

To predict the lifespan, as well to assess the residual resource, it is useful to resort to calculation methods given in [1, 5, 26, 27], which is can be used to create a unified methodology that allows to assess the rate of all wear mechanisms in a large range of operating conditions, such as the high temperature of rock mass.

4 Conclusion

The conducted review showed the lack of details regarding methods to assess wear rate. Techniques that take into account several mechanisms of the high-temperature wear of the operating tools are practically not found in scientific literature. Based on this, the following is concluded:

1. The assessment of thermal fatigue does not used in many methods of evaluating of lifespan and residual resource of operating tools working in high-temperature environment;
2. It has been established that under the high-temperature operating conditions of mining equipment, the dominant factors in the loss of the resource of operating tools are adhesion, abrasion, and thermal fatigue;
2. The study of the mathematical basis of the wear mechanisms presented in the sources is necessary to create a mathematical model to determine the residual resource of the operating tools in a way of study the development of high-temperature abrasive wear processes coupled with thermal fatigue.

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