Analysis of changes in hardness of a metal surface layer in areas of high stress and methods of determining residual life of parts for mining machines

I E Zvonarev[1*] and S L Ivanov[1]
[1] Department of Mechanical Engineering, Electromechanical faculty, Mining University, 2, 21st line, VO, Saint-Petersburg, Russia

*E-mail: ZVano@mail.ru

Abstract. The methodological bases for determining the energy resource of mechanical transmissions details for mining machines are considered.. Based on the analysis of the accumulation of damage in metal gears, a method of estimating residual life of coarse-toothed wheels by periodically measuring the hardness of the surface layer of the teeth is justified. The regularities in change of hardness of coarse-tooth gear, conditioned by a change in metal strength properties that take into account the micro- and macromechanisms of plastic and elastic deformation, distortion of the metal crystal lattice with formation and movement of vacancies and dislocations. Experimental setup was built and the results of laboratory experiments are given related to the process of destruction of non-standard samples under different loads. Comparison of dimensions and hardness values of the sample allows concluding that a larger deformation corresponds to a greater increase in hardness, their limit value for the material being in the fracture zone. It is established that the detected changes in the local hardness occurs in areas of increased stresses above the limit of proportionality and the work of fracture forces attributed to dislocations density adjacent to the fracture plane expressed in terms of hardness increment is constant.

1. Introduction

Substantiation of timing of the inspection, mining machinery repairs and writing off is carried out by estimating residual life of equipment components and details. Traditional technological and diagnostic procedures of state mechanical transmissions assessment do not enable to estimate the residual life of gears with sufficient accuracy, to assess their technical condition quickly. Today one of the most promising ways to assess residual life of coarse-grained gear mechanical transmission of mining machinery is control of changes in metal surface layer hardness in areas close to the fracture surface.

2. Theory research

Researches on fatigue failure of metals [1, 2], friction and wear in machine parts show that material of the detail is destroyed upon the critical value of the internal energy, which is typical for this detail, is reached, that is each element of a mechanical transmission has its energy source. Production rate of a resource determines duration of the element work. Energy approach to definition of the resource allows to take into account intensity of machine work both in the whole and its individual elements [3, 4].

Value of an energy source is constant for the same type of machines and determined by properties of material of its parts, drive kinematics, its production technology, and it does not depend on the value of load, if it does not exceed the maximum of allowable limit. Residual life of the details and the timing of the limit state proportionally depend on the power loss in transmission elements. Thus, energy source is a property of a machine drive and can be calculated by formula

$$K_K = \int_0^{T_P} \Delta P(t)dt = const \,, \tag{1}$$

where K_K = the energy source (kW·h); T_P = the resource of machine drive work (h); $\Delta P(t)$ = the function of the power losses in the drive for a time t (kW).

However, with this approach the whole drive is seen as «black box», and physical nature of fracture process is not considered, which does not enable to identify effectively causes of possible failure and find potentially dangerous elements. This drawback is eliminated in the course of development of an energy source calculation method [5]. In considering the question of an energy source determination of a gear transmission, taking into account all kinds of destruction, energy source value is determined by formula

$$E = \int_a^{N_{lim}} P' dN = \sum_{i=1}^n \frac{N_{lim}^{1-m_i} A_i K_{Bi}}{1-m_i} \,, \tag{2}$$

where $P^`$ – specific power of losses, equal to the work of the dissipative losses in the loading cycle (W); N_{lim}^i – leader-criterion (of the following criterions: $N_{h\,max}$ – number of cycles before the failure by the criterion of the contact strength of the teeth; $N_{f\,max}$ – number of cycles before the failure by the criterion of flexural strength of the teeth; $N_{J\,max}$ – number of cycles before rejection by the wear criterion of the teeth working surface), by which the gear wheel will be broken down; m_i – exponent of the curve energy source equation; A_i – constant coefficient of curve energy source; K_{bi} – coefficient of factors influence for each of the failure criteria: contact chipping, bending strength and wear of active transmission teeth surfaces.

An undoubted advantage of a calculation method for determining an energy source is a possibility of theoretical and experimental evaluation of a resource of such transmission elements as gear wheels, which allows to consider wear phenomena, contact and bending loading of the teeth together, take into account influence of each factor separately for resource of gear wheel in general, depending on the transmission parameters and the properties of each gear wheels.

3. Purpose of research
It is known that the work of fracture is proportional of dislocation density, resulting in a sample under the action of internal stress. Stress, in turn, are reactions to external force. Thus, the specific energy assessment to create a critical density of dislocations in the immediate vicinity of parts fracture plane is possible by periodically measuring the hardness of the surface layer parts.

3.1. Experiments
Experimental investigations of metal surface hardness change in areas of high wear and destruction of mining machines mechanical transmissions parts were carried out at the Department of Mechanical engineering of National university of mineral resources. The measurements were carried out using a universal durometer Zwick ZHU187 (indenter – four-sided diamond pyramid, load – 100 N; soak time – 10 s). Identification of regularities of teeth surface hardness local variation of coarse-grained transmission gears was carried out on the winch gear wheel of career hydraulic excavator lift, worked out about 1.000 machine-hours. Measurements were carried out on 11 teeth wheel (module *m* 8) at the end faces. Methodology for investigation was providing a partition surfaces of each tooth by 76 sectors, within which the measurements were made in the 3-5 points (see Figure 1).

In comparing the obtained results with the model of the teeth stress-strain state during operation it is revealed similarity of changes in local areas of high hardness with a maximum stress of the tooth deformation at a bend (see Figure 2).
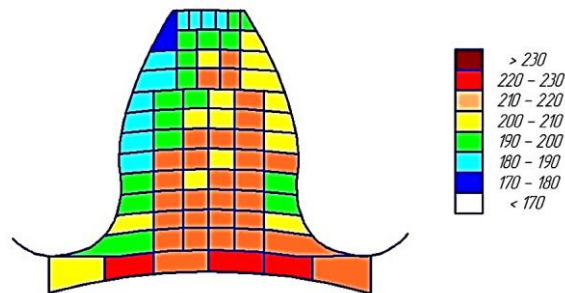
Figure 1. Changes in the surface hardness of coarse-grained gear wheel tooth (module *m* 8 mm, quantity of teeths *z* 19), the nominal hardness is 173HV
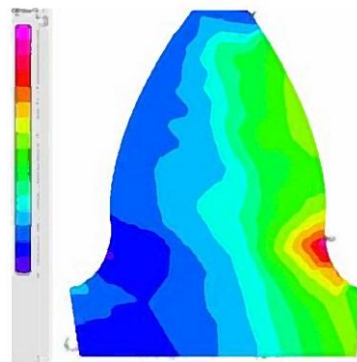
Figure 2. Distribution of principal stresses in the wheel tooth

3.2. Purpose
Identified regularities of hardness change are associated with the process of metals strength properties changing, they allow to take into account micro- and makro-mechanisms of plastic and elastic deformation, causing distortion of the metal crystal lattice with the formation and movement of vacancies and dislocations. Changing of material internal energy density is proportionally to the internal volume of accumulated dislocations. It is not dependent on the loading conditions and it is a physical constant of the material [6].

In working process the gears of mining machines test stress, that causing the different nature of the materials details destruction process. Separation of common energy flow, passing through the gearing in the stress transmission, on the flows, causing the accumulation of the dislocations in the material of the gear wheels, facilitating destruction of the teeth during wear, fatigue failure and fracture of working surfaces of teeth, is difficult [7, 8]. The solution of this problem is possible on the basis of the process researches results of mining machines deformation parts under stress and mechanism of accumulation of dislocations and vacancies in their material.

4. Experimental methods and analysis of results
Investigations of changes in the local hardness in the deformation and destruction of non-standard samples are made by car for static testing Zwick Roell. As a sample for testing was selected a wavy perforated tape – 120.5, made of St10 (see Figure 3). Using the same type of samples with common physical and mechanical properties makes it possible to perform a large number of experiments and high convergence of the results. Periodically changing shape of the samples allows to create different

sizes of stress in one force field on the sample. Non-standard wavy perforated tape – 12×0.5 samples is easily reproducible.
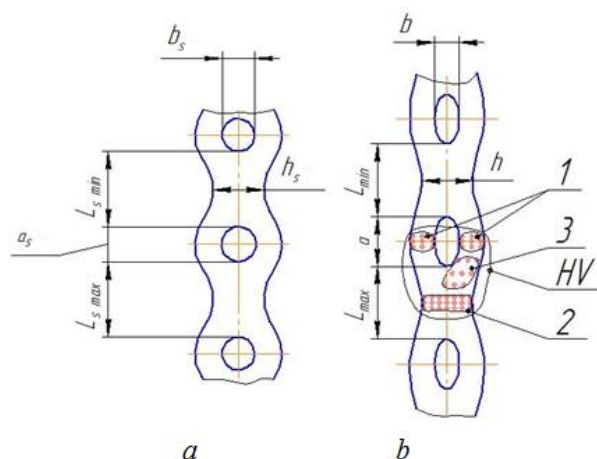
Figure 3. The geometrical dimensions of samples:
a – before stretching; b – after stretching

The first series of five samples was subjected to stretching up to fracture. Average destruction job of five samples line of 210 mm, in static tensile tests on the machine Zwick Roell, is equal to 3.07 J. Battered samples were scanned at the same time, together with the original, undeformed samples from the same batch (five pieces) and a metal ruler (GOST 427-75), chosen as a basis for comparison. Linear measurements were carried out on a computer by the received scanned image in «*Paint.net*» by comparison with the measure in pixels, with subsequent conversion to metric units.

From measurements of geometrical dimensions before and after the fracture it has been found that the dimensions of the ellipse axes a and b (Figure 3b) changed to 41.7% and -29.7% respectively of the values in the original samples. Hole dimensions of samples from the first from fracture plane vary linearly, approaching in the future to the appropriate sizes of the original sample.

However, the dimensions between axes L_{min} and L_{max}, and the width of the connection element h were changed by only 6.9; 3.2 and 0.12% respectively, for the element h it is within the accuracy of measurement. It indicates, that the sample in the area of element h has not undergone a significant deformation, elongation of the sample out of holes is minimal, and portions of samples in areas of the holes undergone deformation. The dangerous section of the sample is also situated there.

Measurements of destroyed and original samples hardness were carried out together with measurements of geometrical parameters of the samples. The zones of hardness measurements of the surface layer are indicated on Figure 3b:

1. In the line of ellipse axis b, and in parallel lines departing from the original till 1.5 mm. The choice of this area is caused by the fact that the destruction of all five samples, subjected to tension, occurred in it. Total 18 measurements for each hole is performed (see 1, Figure 3b).

2. On the line corresponding element h, and in parallel lines extending from the original till 1.5 mm. This area is probably dangerous, as it is the smallest in the area L between the ellipses. There are only 21 measurements on each bridge (see 2, Figure 3b).

3. On the middle line of the envelope hole. The measurements occurred on three lines, which are equidistant of holes samples internal surfaces and equidistant from each other, on three measurements in the each area, totally nine measurements for each element (see 3, Figure 3b).

The obtained results of measurements were processed using methods of mathematical statistics (see Figure 4).
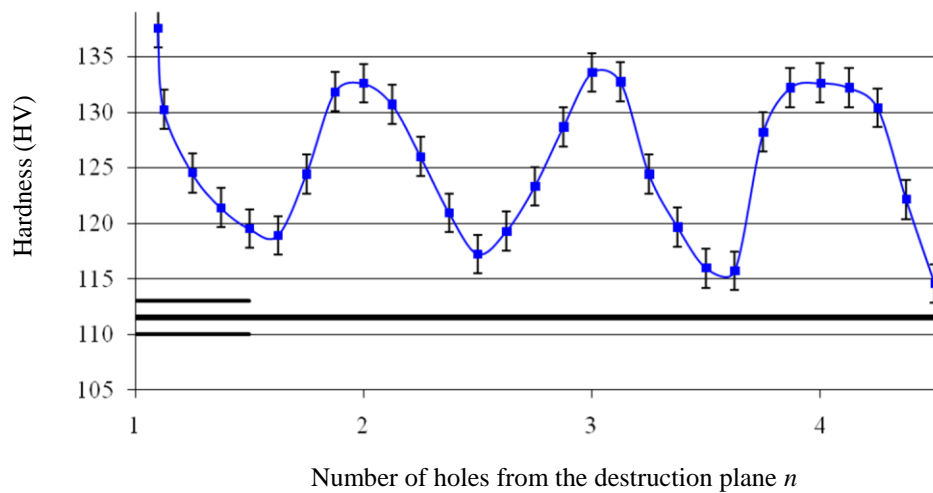
Figure 4. Change in hardness of the samples that were destroyed by car for static testing Zwick Roell compared to the baseline value $HV_S = 115.5$ HV

Change in the hardness of the sample material from fracture plane to the periphery is wavy contour with maximum values of hardness in the area of perforation (see. 1, Figure 3b) and the minimum in the area of the sample restriction (see. 2, Figure 3b).Comparing changes in the geometric dimensions and hardness values of the sample, it can be concluded that the greatest deformations correspond to a greater increase in hardness, which maximum is in the fracture zone.

At the same time with laboratory experiments on a break it was planned to expose the samples to alternating sign bending. For this purpose the stand (physical pendulum), that represents a simulation model of dissipative energy flows in the tooth during operation of the gear wheel, was projected and made (see Figure 5).
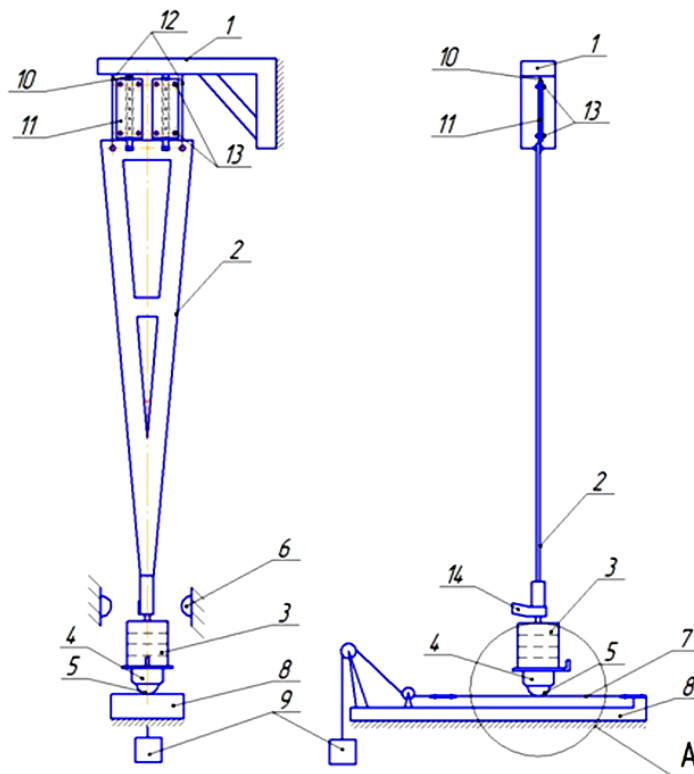

Figure 5. Stand for research of the effects to samples of alternating bending loads

Stand contains pendulum 2, made in the form of an isosceles triangle with an apex angle from 0 to 30°, with a load 3. Grip 4, in which sample, indenter or tool 5 can be installed, is fixed on the pendulum. The sensor of motion controls of the pendulum 6 is connected to the computer by flexible element 7, fixed to the carriage 8, mounted on the lower part of the frame, and provided with a tension device 9 and the gripper 10. The pendulum is rigidly connected to the frame 1 at the point of hanging with possibility of installation between them a sample [9].

Tooth wheel (gear) during operation in engagement experiences bending loads, wear of active tooth surfaces is a consequence of contact loading. Pendulum stand allows to simulate the dissipative losses of separately taken gear wheel of pair, at that the bending stresses of the samples, installed in the grips of the stand, correspond to teeth bending stresses, stretching loads of samples simulate the contact stresses, and the effect of friction in engagement corresponds to the sliding process of the lower roller, mounted on a pendulum, through the surface of the carriage friction element. To estimate the influence on the balance of each elements dissipative loss it is possible to determine their element-wise. At the same time it is possible to combine the dissipative losses in an arbitrary combination.

For fracture of samples by pure bending it is necessary to fix patterns 10 only in the upper part of the frame 1, and the whole structure of the pendulum will be suspended on weightless inextensible threads 13, thereby allowing the sample testing only bending loads during oscillations of the pendulum, which will simulate the bending stresses in the tooth upon engagement in gearing of mining machine.

If the samples 10 to fix both the upper part of the frame 1 and the pendulum 2, the threads 13 are loosened and the entire structure of the pendulum is suspended directly on the samples themselves, thereby additory burdening them by elongation at oscillations of the pendulum and simulating the contact pressures in engagement of wheel transmission.
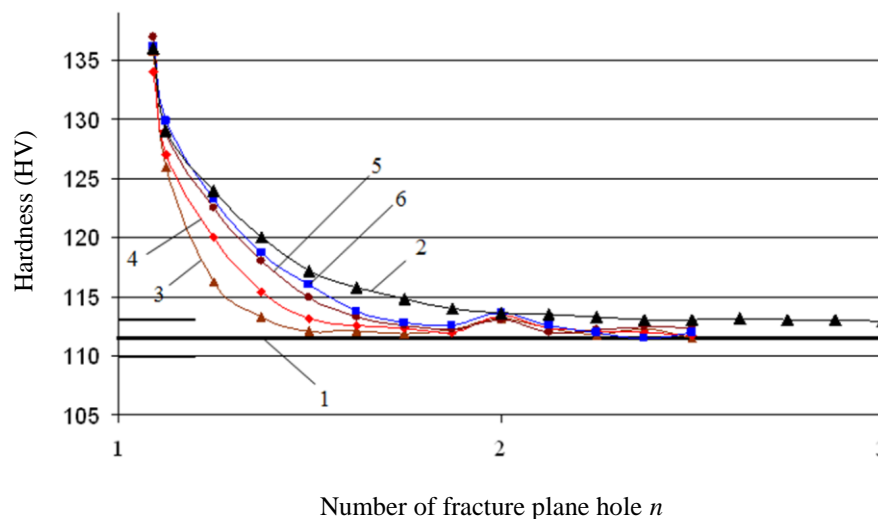
Figure 6. Distribution of hardness along the length of the original sample and destroyed on pendulum stand at an initial deflection angle of 30° 3': 1 – the surface hardness of the initial sample; 2 – the surface hardness of the sample, which was destroyed by the action of bending loads only; 3-6 – the surface hardness of the sample, which was destroyed by the action of bending and stretching axial loads 51.15; 41.15; 31.15 and 21.15 N, respectively

Several series of experiments (seven tests under the same conditions), in which the samples were subjected to loading by pure bending and bending with stretching under the influence of pendulum gravity that is equal to 51.15; 41.15; 31.15; 21.15 N respectively, were produced. The initial deflection of the pendulum was 31° 3'. As a result of the experiments, all the samples were destroyed, at that the

number of blocks of variables loading cycles, the number of cycles in a block, the block loading time were fixed and the temperature and humidity to assess the resistance to motion of the pendulum on the air were measured. Thus measured facts was used for further assessment of samples destruction.

Destroyed samples in the pendulum by bend were subjected to measures of the surface layer hardness from the plane of destruction to place of sample fastening in stand by the same method as the samples that were destroyed by stretching (see. Figure 3b). Results of samples hardness measurements were processed by using methods of mathematical statistics (Figure 6).

In the figure 6 the line 2 corresponds to pure bending. Hardness value gradually decreases from the maximum to the nominal value within one link of the sample. Line 3 characterizes the combined effect of bending and stretching loads under the effect of pendulum gravity 51.15 H, change of hardness is more sudden, but there is a small increase in hardness in the area of the first hole from the plane of fracture.

Analysis of the graphs, shown in Figures 4 and 6, allows to draw following conclusions: regardless of the method of loading in the immediate proximity to the fracture plane hardness values are approximately the same, suggesting that failure occurs in the volume of material when it is get the certain accumulation of dislocations in the crystal lattice [10].

Clean work of samples fracture with allowance for dissipation of system for motion in the air was: 1.69 J (51.15 H); 2.288 J (41.15 N); 2.81 J (31.15 N); 3.032 J (21.15 N). There is the effort equivalent to construction gravity of pendulum with load in parentheses. The value of the specific fracture energy, referred to the dislocation density, expressed in hardness value of the surface layer in the fracture zone, can be assumed a constant value within the experimental accuracy, which is 0.023 J, that does not contradict the theory of energy and fracture kinetics [11, 12].

5. Discussions

Despite the fact, that the accumulation of damage and, consequently, an increase in the hardness of the material detail surface layer, is not a necessarily monotonically varying process [13, 14], we can assume, that the process has a certain constant speed during the time interval (or operating time), significantly exceeding cycle of power impact [15]. During the steady flow of damage accumulation process, knowing the actual value of hardness, for example, the end surface of the tooth, identified through diagnostic procedures, and determine maximum hardness value for the fatigue sample of the test material, it is possible to estimate the conditional residual life of the tooth on the criterion of fatigue bending strength:

$$T_{YFP\,res} = T\left(1 - \frac{\Delta HV_F}{\Delta HV_{MAX}}\right), \tag{3}$$

where T_{YFPres} – the conditional residual life of the gear wheel according to the criterion of fatigue bending strength (h); T – the resource of the transmission, it can be calculated using standard methods or determined experimentally for specific operating conditions (h); ΔHV_F – the increment of the hardness of the surface layer of the tooth end surface in the dangerous section of (HV); ΔHV_{MAX} – the maximum possible (dangerous) increment of the end surface hardness of the tooth in relation to the initial state (HV).

Conditional value of residual life according to the criterion of wear will be determined similarly:

$$T_{YP\,res} = T\left(1 - \frac{\Delta S}{[S]}\right), \tag{4}$$

where T_{YIPres} – conditional residual life of the gear wheel according to the criterion of wear (h); ΔS – wear amount at the time of the events on the diagnosis (mm or kg or m^3); $[S]$ – allowable wear (mm or kg or m^3).

Control of surface hardness of the tooth working surface allows to estimate the ratio of the wear and fracture processes according to the criterion of surface contact fatigue of the teeth. If the surface layer hardness of the teeth working surfaces does not change, wear process dominates.

If it is required to estimate the conditional residual life according to the criterion for contact endurance, it should be evaluated similarly to the expression (3), but considering the fact that the process of wear and damage accumulation of contact fatigue occurs within one and the same surface:

$$T_{YH\text{Pres}} = T\left(\frac{\Delta HV_H}{\Delta HV_{MAX}}\right), \tag{5}$$

where T_{YHPres} – conditional residual life of the gear wheel according to the criterion of the contact endurance (h).

As all three degradation processes take place simultaneously, for coefficient assessing of influence one of the three kinds of gear wheel destruction (expressions (3)–(5)), it is expedient to use the relation

$$K_{Bi} = \frac{T_{Yi\text{Pres}}}{\sum T_{Yi\text{Pres}}}, \tag{6}$$

where K_{Bi} – coefficient characterizing the distribution of the wear types.

Further, in the multiplication of both sides of the expressions (3)–(5) to the corresponding value of coefficient K_{Bi}, at one time with assessment of the three factors influence of the fractures the assessment of residual life is realized directly by fixed diagnostic parameters.

6. Conclusion
From the above mentioned it follows, that the value of the fracture specific work, relegated to the value of the dislocation density, expressed in terms of the surface layer hardness value in the fracture zone, is constant. Thus, the residual life of mining machines details can be determined with high accuracy on the results of change in the surface hardness of the local areas, in particular, the ends of the gear wheels. Perhaps the solution of the inverse problem is the experimental determination of potentially dangerous cross sections by the areas localization of surface layer increased hardness. It should be noted, that the surface hardness of the sample exposed to stresses, varies according with change in the stress state and reaches the maximum in the fracture zone. Accumulation disorders (dislocations) in the sample under uniaxial tension decreases with increasing distance from the plane of the fracture. The value of the sample maximum hardness in the area of the fracture plane does not depend on the method of destruction and determines by limit value of disorders (dislocations) in the sample material.

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