

## Modern Approaches to Monitoring the Technical Condition of Heavy-Duty Gears

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### Abstract

**INTRODUCTION:** Gear transmissions of heavy-duty drive reducers operate under variable loads that cause fatigue damage (pitting and tooth fracture), therefore effective condition monitoring is essential to prevent failures..

**OBJECTIVES:** To conduct a review of the directions and methods for monitoring the technical condition of gearbox gears, to select an appropriate monitoring approach for the gears of high-power machine drives, and to propose the most effective method taking into account operating conditions and gear tooth control zones.

**METHODS:** The research employs an instrumental monitoring approach based on measuring the surface hardness of gear teeth using portable hardness testers. The methodology involves comparative analysis of metal hardness in two critical zones: the tooth end faces and the working surfaces.

**RESULTS:** Based on the conducted review, a method for monitoring the technical condition of gearbox gears in high-power drives has been developed. This method can be applied both in workshop and field operating conditions, enabling inspection of the working and non-working tooth surfaces with or without gearbox disassembly.

**CONCLUSION:** The developed monitoring method for gearbox gears of high-power drives will serve as a foundation for the development of a method for predicting the remaining service life of gearbox gears in high-power machine drives.

**Keywords:** Gearboxes, Heavy-Duty Gears, Methods of Technical Condition Monitoring

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### 1. Introduction

Gear transmissions of high-power drive gearboxes used in heavy machinery and mechanisms are critical units that convert the rotational motion of a motor into extremely high torque with reduced speed to drive the working elements of mining and lifting equipment, railway transport, and rolling mill machinery.

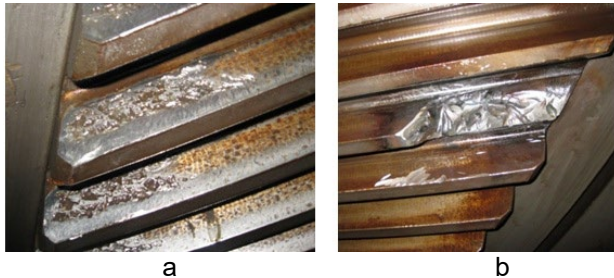
The gears of such gearboxes operate under extreme conditions of variable loading, which leads to the accumulation of fatigue damage followed by the formation of microcracks and eventual failure. The process of fatigue damage accumulation in gears is

influenced by design factors (stress concentration), technological factors (material microstructure and defects), and operational factors (load frequency and cycle asymmetry).

The first signs of fatigue damage accumulation are changes in the physical and mechanical properties of the material, resulting in the formation of plastic zones. Plastic zones may appear on the working flanks in the vicinity of the pitch point and at the tooth root in the transition area between the tooth and the gear body due to the complex nature of loading.

In the first case, surface fatigue pitting of the tooth flanks occurs (Fig. 1a), which is associated with cyclically

varying stresses and represents the primary type of damage in gearbox gears. In the second case, tooth breakage occurs (Fig. 1b), which is the most dangerous type of gear transmission failure; it arises from the prolonged action of alternating bending stresses as well as significant static or impact overloads.



**Figure 1.** Tooth damage: (a) pitting; (b) fracture

Therefore, the selection of an appropriate direction and method for monitoring the technical condition of gears is highly relevant in order to prevent their failure.

## 2. Literature review and problem statement

Various approaches to monitoring the technical condition of gear transmissions are widely used. Vibration-based monitoring is one of the most widespread methods [1], which involves acquiring a vibroacoustic signal from the gearbox housing. This signal, containing extreme values of the linear deformation function for each tooth in the phase domain, is compared with a permissible deformation parameter determined from previously established results of standard gear transmission tests. Vibration diagnostics for the technical condition of drive gear mechanisms has been further developed through the analysis of impact processes in gear transmissions [2]. However, as noted in [3], the accuracy of assessing the current technical condition and the reliability of defect diagnostics in gear pairs based on vibroacoustic signals largely depend on the operator's experience, knowledge of the internal structure of the monitored equipment, and understanding of the nature of the vibration processes. Despite the extensive development of numerous signal processing and analysis methods, as well as software and hardware diagnostic tools, fault identification still contains a significant degree of subjectivity; furthermore, the diagnostic process remains time-consuming, labor-intensive, and is primarily applicable to high-speed gears.

Recent studies demonstrate further development of vibration-based monitoring through machine learning and deep learning approaches for gearbox diagnostics. In particular, intelligent fault diagnosis methods based on transfer learning and advanced feature extraction have shown high efficiency in identifying gearbox defects under variable operating conditions [4, 5]. However, these

methods still require specialized sensors, signal processing procedures and large datasets for model training, which complicates their application for slow-speed heavily loaded industrial gearboxes.

When selecting a method for monitoring fatigue damage of the working (contacting) surface layers of gear teeth, it is necessary to consider the feasibility of conducting investigations under field or workshop conditions using portable and relatively simple equipment. Under these constraints, an instrumental monitoring approach has been selected, for example, methods based on measuring changes in the physical and mechanical properties of the tooth material.

Fatigue damage assessment is often performed using the Vickers microhardness measurement method, which requires careful surface preparation and is not always feasible for large-scale components in real operating conditions. Therefore, publication [6] demonstrates the application of the Brinell macrohardness measurement method for monitoring the technical condition of metal. The applicability of Brinell hardness measurements for gas pipeline elements under operating conditions is shown in [7], where threshold hardness values corresponding to the maximum permissible plasticity coefficient were established.

The possibility of detecting fatigue damage by measuring surface hardness at different stress amplitude levels has been confirmed in [8]. The relationship between hardness and plastic deformation of structural steel elements in building beam connections was established in [9]. Other publications allow the determination of material structure [10] and porosity [11] based on hardness measurements. Further development of metal condition monitoring methods is presented in [12, 13]. In [12], adapted methodologies are provided for assessing fatigue damage accumulation in steels subjected to randomly varying load amplitudes, based on the LM-hardness method and the limiting cyclic plasticity exhaustion model. In [13], experimental results are presented on the applicability of the LM-hardness method for evaluating damage processes in steels of various classes under cyclic loading with different cycle parameters (stress amplitude, mean stress, loading frequency), with fatigue damage assessed according to the PNAE standard methodology.

Gears with large modules ( $m \geq 10$  mm) are widely used in heavy engineering, for example in rolling mills. Unpredictable overloads of mechanical equipment or operator errors often lead to premature failure, primarily of typical components such as gears. The application of hardness-based technical condition control for large-module gears was first demonstrated in [14], where regularities in hardness variation were identified, associated with changes in metal strength properties and accounting for micromechanics of plastic and elastic deformation and crystal lattice distortion. It was established that the observed changes in local hardness occur in regions where stresses exceed the proportional limit.

However, the hardness variation method requires further refinement regarding the number of tests, the number and spatial arrangement of measurement points, since the adequacy of the resource exhaustion function depends on these parameters. Therefore, publication [15] proposes a diagnostic method based on changes in hardness at the gear tooth end faces in potential fracture zones, recommending at least five tests on a single tooth at equal time intervals, with three to five measurements per test taken at minimal mutual spacing of at least three indentation diameters from the hardened layer. In practice, this method required further refinement: measurements should be performed not on a single tooth but on at least five adjacent teeth [16]. The proposed technical solution improved the reliability of in-service diagnostics of gears based on hardness measurements in potential failure zones.

A procedure for monitoring the technical condition of heavily loaded gears based on the level of accumulated fatigue damage during operation and a methodology for predicting guaranteed failure-free service life are presented in [17]. The applicability of two promising monitoring approaches – based on metal hardness and on parameters of the magnetic field intensity of gear tooth metal – was analyzed. However, this combined approach requires modernization of existing magnetic inspection equipment to refine measurements on gears.

In [18], an algorithm is proposed for modeling the technical condition control of large-module gears through hardness measurements in several hazardous local zones. The theoretical basis of the monitoring process is a functional model incorporating design, technological, and operational factors, structured around cyclically repeated procedural stages and measurement steps. A promising direction is monitoring based on artificial intelligence [19], using two methodological types of machine learning approaches: feature engineering and feature learning (deep learning). This approach is applied in studies of gear wear based on vibrodiagnostic signals.

Modern condition monitoring systems also employ entropy-based wear classification methods and advanced feature engineering techniques to improve gearbox fault identification and predictive maintenance capabilities [20,21]. Nevertheless, these approaches remain primarily focused on vibrodiagnostic signals and require substantial computational resources.

The analysis of the literature indicates that, for assessing fatigue damage of many technical objects under operating conditions, vibration diagnostics and surface hardness measurements are most commonly used, both of which require further methodological and instrumental development. Therefore, the problem identified by the authors – selecting an appropriate monitoring direction and methods for large-module gears under operating conditions, both without and with gearbox disassembly – remains unresolved.

Acoustic emission methods are also increasingly applied for monitoring active surface degradation and wear processes in gears due to their high sensitivity to

local tribological changes [22,23]. Experimental studies demonstrated the capability of acoustic emission signals to identify surface degradation and wear progression in planetary gears. However, implementation of acoustic emission monitoring in industrial heavy-duty gearboxes requires dedicated high-frequency sensors and complex signal interpretation procedures. Therefore, hardness-based monitoring remains attractive for field applications due to its simplicity and applicability during scheduled maintenance.

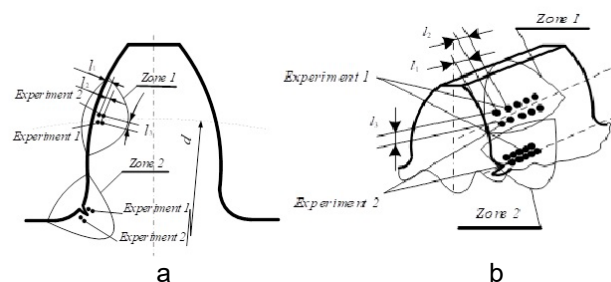
Unlike the earlier studies and patents [15–18], which mainly addressed separate diagnostic procedures, hardness measurements in individual tooth zones, or conceptual models of monitoring, the present study proposes an integrated monitoring methodology combining hardness measurements in both working and non-working tooth regions. The proposed approach is specifically adapted for industrial heavy-duty large-module gears and allows inspections under operating conditions both with and without gearbox disassembly.

Thus, the aim of this work is to review the directions and methods for monitoring the technical condition of gearbox gears, to select an appropriate monitoring approach for the gears of high-power machine drives, and to propose the most effective method considering the operating conditions of the machines and the gear tooth inspection zones.

To achieve this aim, it is necessary to: conduct a review and analysis of the literature on the monitoring of gearbox gears' technical condition; and develop a method for monitoring the technical condition of gears in high-power drives that is suitable for both workshop and field operation, allowing inspection of the working and non-working tooth surfaces with or without gearbox disassembly.

### 3. Development of a method for measuring gear tooth hardness

It is proposed that the monitoring of the technical condition of gear teeth during operation be carried out by measuring the metal hardness in two zones of potential failure – at the tooth end (Fig. 2a) and along the working surface (Fig. 2b) – during scheduled preventive maintenance stops of the machine.



**Figure 2.** Schemes of tooth hardness measurements: (a) on the end face; (b) on the working surface

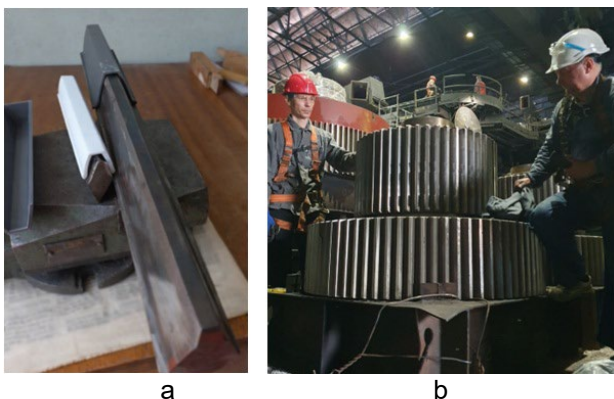
The first potential failure zone of the teeth is located at the pitch diameter  $d$  of the gear, and the second is near the tooth base (root).

Measurements on the end faces and on the working surfaces of the teeth were carried out, firstly, in at least two test zones located adjacent to each other; secondly, at least twice for each test zone; and thirdly, the measurements were performed at a distance of not less than three indentation diameters  $d_{(v)}$  from the hardened layer  $l_1$  and from each neighbouring measurement both in depth  $l_2$  and in width  $l_3$ . The indentation diameter, for example when using the portable hardness tester UIT Constanta KT, does not exceed 0.45 mm. Therefore,  $l_1 = l_2 = l_3 \geq 3d_{(v)} (\approx 1.5 \text{ mm})$ .

For each measurement zone, hardness values were obtained from repeated measurements and processed statistically. The mean hardness value and standard deviation were determined to improve repeatability assessment and reduce the influence of local material heterogeneity. The repeatability of measurements was ensured by repeated tests in each control zone and by maintaining the minimum spacing requirements between indentations.

Measuring the hardness of teeth at the ends ensures control of the gear’s technical condition throughout the entire regulated service life (e.g., one year) without dismantling the gearbox, while measuring the hardness along the working surfaces is performed before placing the gear into operation and after its removal from service.

The developed method for measuring tooth hardness was tested on cut teeth (Fig. 3a) from a rejected gear (Fig. 3b) of the vertical roll drive gearbox of the “Slabbing-1150” mill.

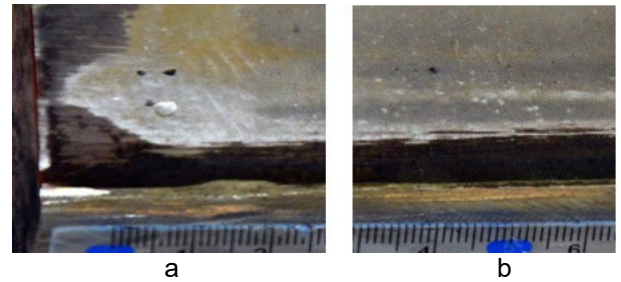


**Figure 3.** Cut tooth (a) from a rejected gear (b)

The wear analysis of the gear teeth working surfaces was carried out for a gear removed from service after one

year of scheduled operation. Since the gear operates in a reversible mode, the analysis was performed for both sides of the teeth (designated as A and B) along the entire length (450 mm), with local zones highlighted (up to 150 mm).

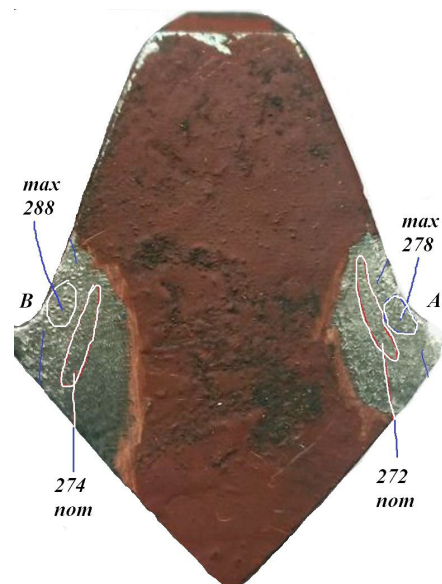
Below are the most characteristic photos of the gear teeth from the gearbox, showing various pitting areas for sides A and B (Figs. 4 and 5), as well as on the end surface (Fig. 6).



**Figure 4.** Areas of the tooth with pitting (side A): a – area 0...30 mm; b – area 30...60 mm

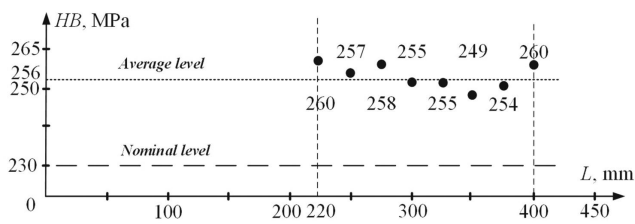


**Figure 5.** Tooth area (350...450 mm) showing the final traces of pitting (side B)



**Figure 6.** Tooth end with measured hardness values

The results of hardness measurements of the gear's working side surfaces are shown in Fig. 7.



**Figure 7.** Hardness measurement results in the pitting zones

## 4. Discussion

The wear analysis of the working surfaces of the intermediate gear teeth in the reversible gearbox of the vertical rolls of the “Slabbing-1150” rolling mill showed that the B sides, corresponding to the forward movement of the slab, experience more severe damage. Local isolated pitting of both large and small sizes on the tooth surfaces indicates the onset of contact fatigue failure, while plastic dents may be caused either by insufficient oil filtration or by random hard particles introduced during cleaning. The absence of edge impact marks on the tooth surfaces indicates the effectiveness of tooth flank design.

The possibility of monitoring the technical condition of gears by measuring the hardness of the tooth working surfaces in the polar zone and of the end surfaces in the radial transition areas of the tooth valleys has been confirmed. An increase in hardness in these zones compared to the nominal hardness at a distance from the contact points and stress concentrators was established.

The observed increase in hardness in local pitting regions confirms the relationship between accumulated plastic deformation, local strain hardening, and fatigue damage progression. Therefore, hardness variation may be considered as an indirect indicator of fatigue accumulation and used as a basis for predictive maintenance approaches and future remaining useful life estimation models.

The asymmetrical distribution of pitting relative to the gear ends indicates gear misalignment during operation. The identified cause of gearbox gear misalignment points to the need for design improvements to minimize the misalignment angle. This, in turn, requires specialized studies of the statics and dynamics of the gear assembly.

The present study represents an industrial pilot validation performed on the “Slabbing-1150” gearbox. Extension of the methodology to other gearbox designs, materials, and operating conditions will be addressed in future studies involving multiple gear types and service conditions.

## 5. Conclusions

Based on the analysis of literature data on monitoring the technical condition of gearbox gears, a promising approach has been identified for monitoring the gears of high-power machine drives, which is implemented through measuring the hardness of the gear tooth material.

- The feasibility of monitoring the technical condition of gears by measuring the hardness of the tooth working surfaces in the polar zone and the end surfaces in the radial transition area of the tooth valleys has been demonstrated.
- Two promising methods for monitoring technical objects based on the accumulated fatigue damage during operation have been identified – by metal hardness and by parameters of the external magnetic field intensity.
- A method for measuring tooth hardness on the working surfaces and at the tooth ends has been proposed; these approaches complement each other and can be applied under operational conditions both without and with gearbox disassembly.
- The methodology for monitoring the technical condition of large-module gears using the developed method of measuring tooth hardness on the working surfaces and ends was tested on a gear from the vertical roll gearbox of the “Slabbing-1150” rolling mill. The developed method can be applied in industrial conditions for machines with gearboxes that have large-module gears.
- The accuracy of monitoring the technical condition of large-module gears is planned to be improved by applying a method for evaluating the magnetic field stress of the gear tooth metal.
- The conducted study provides the basis for integrating hardness-based monitoring into predictive maintenance systems through periodic condition assessment, trend analysis of hardness evolution, and future development of remaining useful life estimation models for large-module gears.

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