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STUDY OF THE FUNCTIONING AND WEAR OF THE TEETH OF THE INTERMEDIATE GEAR OF THE VERTICAL GEARBOX ROLLS OF THE SLABING STATE - 1150

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Abstract

Gears with large modules are widely used in heavy engineering, for example in rolling mills. The unpredictability of mechanical equipment overloads or operator error lead to premature failure, first of all, of typical parts like gear wheels. This article analyzes the nature of the wear of the working surfaces of the teeth of the most problematic second stage of the intermediate gear of the gearbox of vertical rolls of Slabbing-1150 PJSC "Zaporizhstal" with the aim of identifying the features of the operation of the gear in order to improve the methods of its calculations and construction, choosing a method of monitoring the technical condition and evaluating the residual resource. A simple and reliable method of monitoring the intermediate gear by measuring the hardness in workshop operating conditions was chosen. The method of estimating the residual life of gear wheels with large modules and possible ways of increasing the reliability of the intermediate gear of the vertical roller gearbox are discussed.

Keywords: rolling mill, gearing, types of wear, resource, monitoring.

1. INTRODUCTION

The object of consideration belongs to the family of gearboxes with many engines, which are more often used for heavy equipment in the mining, metallurgical, and chemical industries, where technological processes and significant torques limit the use of gearboxes of a traditional design.

Gear gearbox with four motors for Slyabing-1150 mill vertical rolls of PJSC "Zaporizhstal" is one of the most problematic nodes, as it has a limited resource due to the destruction of the teeth of the intermediate gears. This gearbox is under severe dynamic load conditions caused by the technological process of periodic capture and ejection of massive steel ingots by rolls. The effect of multiple clearances, variable in time due to wear, in kinematic pairs of mechanical systems and insufficient reliability of bolted fasteners contribute to additional dynamic loads of gearboxes. The especially harmful effect of clearances is observed due to cases of imbalance of electric drives operating in parallel. The insufficient reliability of these gear gearboxs is also associated with the difficulties of uniform technological strengthening of gear wheels with large modules, which reduces their endurance in contact and when bending, increases wear.

When designing gearboxes, the issues of accounting for the wear of wheels, the stiffness of bearings and shafts, the imbalance of spindles and roller couplings on their operation, for example, the formation of shaft distortions, and therefore the redistribution of contact stresses in gear engagements, remain unresolved. Standard design methods do not provide answers to such questions that arise during operation, which, in combination with a large dispersion of technological loads from calculated values, leads to a low durability of the equipment, and the safety factors used in practice when calculating gearboxes (usually at the level of 1.5 ... 2.5) do not meet the operating conditions of rolling mills.

The analysis of gearboxes produced at the PJSC "Zaporizhstal", entering the "Slyabing-1150" state, showed a variation in the hardness of the wheel material up to 12%. Due to the lack of reliable data on the remaining life of the intermediate gears, the maintenance services must keep double sets of them in warehouses and remove them from operation after one year of operation.

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The study of the operation and nature of wear of the teeth of the intermediate gear of the gearboxes of the vertical rolls in the hot rolling state is aimed at identifying the peculiarities of their operation in order to clarify the methods of strength calculations, increase reliability, and find the most acceptable way of monitoring the technical condition and estimating the residual resource.

In this work, a study of the nature of the wear of the teeth of the intermediate gear of the reducers of the vertical rolls in the hot rolling state is carried out on their operation and is aimed at identifying the peculiarities of their operation in order to clarify the methods of strength calculations, increase reliability, and search for the most acceptable method of monitoring the technical condition and estimating the residual resource.

The complex nature of the load on the teeth of gear wheels is the cause of wear of the teeth, and as a result of possible destruction. The most characteristic types of destruction of the surface layers of the teeth are fatigue cracking, peeling, abrasive action, and seizing. Fatigue cracking of the active surfaces of the teeth is related to the action of cyclically alternating stresses and is the main type of damage to gear wheels, when the lubricant accelerates the process of destruction by pressing it into the initial surface damage. Exfoliation of the metal on the surfaces of the teeth is observed when the quality of the heat treatment is not high enough due to significant overloads. Seizure is observed mainly in highly loaded gears, when a high temperature develops in the contact zone of the teeth, which causes the destruction of the lubricating film and the formation of direct metal contact, adhesion of metal particles, their separation from a less durable surface with burrs of the working surface of the tooth in the direction of sliding. Abrasive engagement of teeth happens

in gears with insufficient lubrication due to deterioration of lubricant properties or in the presence of wear products or foreign particles of the surrounding environment.

2. ANALYSIS OF LITERARY DATA

It is known that the functioning and service life of gears are influenced by design and operational factors. The publication [1] gives the results of an experimental and theoretical study of the influence of gear modification to reduce gear vibrations on their dynamic characteristics. The effectiveness of the method of analysis based on the model for calculating the stiffness of the teeth, which includes the measured and accumulated errors of their profiles, is shown. In the publication [2], the displacement of the shaft and the sliding friction between the transmission teeth on its vibration were investigated. The effect of shaft misalignment on the friction of the teeth and their stiffness was studied by computer simulation. The operation of the helical gear according to the dynamic model, which takes into account the errors of the tooth profile, was studied in [3]. It is shown that the relief and misalignment of the gears reduces the rigidity of the engagement. Methodology for predicting surface wear for spur gears proposed in [4]. The methodology combines the finite element method and the Archard formula to predict the surface wear of a gear pair. The results of the study showed that shifting or misalignment of wheels can worsen the state of load distribution and accelerate their wear. The effect of modification of the tooth profile of cylindrical gears and installation errors of gear wheel shafts on the functioning of the transmission was studied in [5]. According to the results of the study, it was established that the modification of the profile of the teeth reduces the harmful effect of misalignment of the shafts. The study of the nonlinear characteristics of the vibrations of the gear train taking into account the proposed fault function entered into its dynamic model was carried out in [6]. This approach allows early prediction of the appearance and functioning of gears with various types of damage. Damage to open gears of layer mills for grinding ore and coal was considered in the work [7], where the types of wear and the causes of their appearance were analyzed, and the approaches to increase reliability were critically analyzed. The method of detecting damage to gear wheels using artificial intelligence is presented in [8]. In the publication [9], instead of a visual inspection of damaged gears, it is proposed to measure the topography of worn surfaces with micropitting, pitting, abrasive wear by the method of light interferometry, and the damage itself was assessed by roughness parameters. The methodology of computer assessment of the mechanism and degree of damage, which includes surface replication, visualization and recognition of damage, is proposed in [10]. This methodology is based on the theory of neural networks using a damage data bank. An original approach to obtaining complex information about the evolution of wear based on the method of non-contact two- and three-dimensional measurement without disassembling the gearbox is proposed in [11]. Measurements are performed using optical and laser devices with subsequent processing according to parameters of roughness and depth of wear. The publication [12] proposed a method of estimating the depth of wear from a two-dimensional image based on a hybrid model of a neural network that forms a three-dimensional topography. Testing of the proposed model by experiment showed a calculation error of no more than 19%. In the review [13], a group of methods for measuring surface roughness based on artificial intelligence is considered. Image analysis and a scanning electron microscope were used in the publication [14] to measure gear teeth wear. Measurements that include a combination of contact and non-contact methods are, in the author's opinion, the most effective. The research carried out in [15] offers an approach for monitoring and predicting changes in surface profile and pitting density in spur gears of a gearbox connected to an induction motor. This approach considers three main steps, starting with a dynamic gear model with 21 degrees of freedom to simulate the element response, using two tribological models that estimate wear depth and pitting density, and updating the models by continuously comparing measured and estimated signals. In [16], the use of tribology and vibration signals to develop a model based on a vector model for the fusion of multi-functional characteristics and an index for online monitoring of wear residues are used to evaluate wear and pitting in planetary gears. The method of estimating the ultimate life of gear wheels by periodically measuring the hardness of the surface layer of the teeth is proposed in [17]. It was established that greater deformation corresponds to a greater increase in hardness, especially in places of increased stress. The justification of the method of estimating the final resource of gears by regular measurement of the hardness of the surface layer of the gear metal is given in [18]. The regularities of changes in gear hardness are revealed. The works [19] are devoted to the development of methods for estimating the residual life of gears of gearboxes of rolling mills. In work [17], a method of diagnostics of the power drive of the procurement state and prediction of the residual resource based on the data of the change of gaps in the conjugations of kinematic pairs is proposed. In [18], a procedure for diagnosing the technical condition of gear wheels by measuring metal hardness was developed. In work [19] stationary and non-stationary oscillations of spindle assemblies of metal-cutting equipment, which are installed on elastic supports with adaptive elements of quasi-zero stiffness, are considered. The regularities of the change in the hardness of the gear wheel were revealed. The work [19] is devoted to the development of methods for assessing the operability of the main drives of the blanking mills. In the work [20], a method for diagnosing the technical condition of gear wheels by measuring the hardness of the metal of heavily loaded machines was developed. In the work [21], a review of modern approaches to modeling the control of the technical condition of gear gears during their operation is given. The most appropriate method of controlling the technical condition by the level of accumulated fatigue damage was established.

In the reviewed publications on the study of damage to the working surfaces of gears, gear pairs with straight teeth, having horizontal shafts with symmetrical load relative to the supports, are more often highlighted. In addition, almost all methods of wear research use special equipment, are expensive and technically complex to perform and require significant time for their implementation. The determination of wear characteristics using 3D scanning technology is promising [22, 23]. Scanned surfaces allow you to determine volumetric wear and take into account differences in the physical properties of the material.

3. STATEMENT OF THE PROBLEM

Gears of the gearbox of vertical rolls of the "Slabing -1150" mill PJSC "Zaporizhstal" (Fig. 1) has vertical shafts, one of the supports of which receives the load of the gear, and this definitely affects its operation.

An idea of the gear unit of the drive of vertical rolls state "Slabing-1150" gives a mock-up 3- D image in fig. 1.

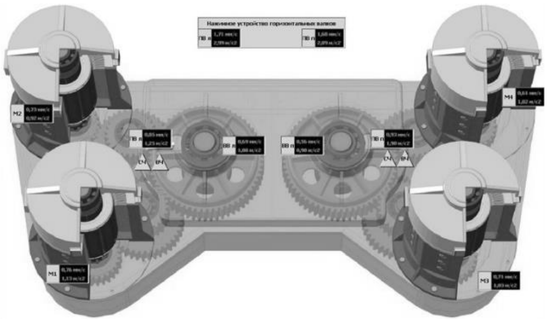


Fig. 1. Layout of the vertical roller drive gearbox

In fig. 2 shows the assembly drawing of the vertical roller gearbox and its kinematic diagram, respectively.

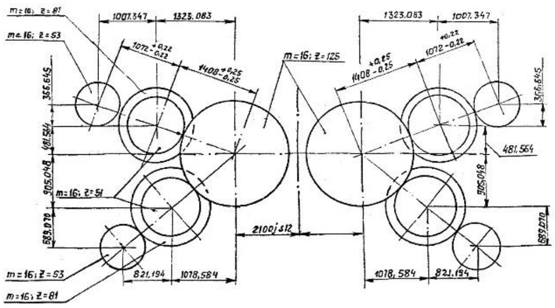


Fig. 2. Kinematic scheme of gear engagement

It follows from the drawings that the gearbox has a symmetrical layout with respect to four electric motors and includes four independent two-stage gear transmissions, each of which has its own independent direct current electric motor with a power of 20,000 kW and a rotation frequency of 500 rpm.

The nominal torque on the output shaft of each gear is 1200 kNm; gear ratio 3.744; the number of revolutions on the output shaft is 133.6 rpm; working mode – reversible 23 hours around the clock; Gear coupling lubricant - liquid circulation oil I100RS; service life of the reducer is 1 hour. All the gears have a module, and the gear pairs have the number of teeth 53×81 and 51×125. Spur gears, involute, accuracy level 7B, tooth material hardness HB 250...310.

The technological process of rolling on "Slyabinge 1150" differs in that the slab is immediately fed from the crimping shop to the hot-rolled shop on the wide-strip sheet mill 1680, implementing transit rolling without additional heating of the slab. Such a progressive rolling process imposes high requirements on the reliability and failure-free operation of all the equipment involved, and this is possible if a highly effective method of periodic control of the most heavily loaded elements is not used.

The experience of operating the slab has shown that the most frequent failures occur in the reducer of the vertical cage, and the most vulnerable elements in it are the gear teeth of the second stage of each transmission. This gear is not only the most loaded, but also the first to perceive all dynamics from the side of vertical rolls.

The calculation schemes of the vertical roller drive gearbox and the intermediate gear are presented, respectively, in fig. 3 and Fig. 4.

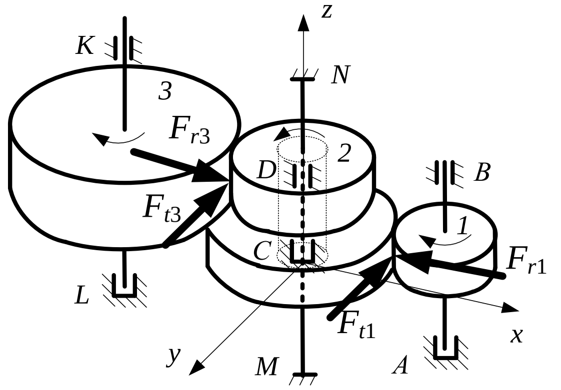


Fig. 3. Calculation diagram of the vertical roller drive gearbox: leading 1 gear with movable supports A and B; intermediate 2nd gear with movable supports C and D and fixed supports M and N; output 3 gear with movable supports L and K; F r 1, F r 3 and F t 1, F t 3 respectively, radial and tangential forces in the engagement poles

The problem link in the gearbox under consideration is the intermediate gear 2. A feature of the design of the intermediate gear unit is two pairs of mounted roller bearings (roller conical in the support C and roller spherical in the support D) rotating relative to the stationary shaft in the supports M, N. The immediate object of the study is the second most vulnerable stage of the intermediate gear (d a = 848; b = 450; m = 16 mm). The axial load G from the weight of the gear is transmitted to the roller conical shafts in support C and are locked on the side of the fixed shaft. Therefore, an asymmetric load on the gear and different stiffnesses of the shafts of supports C and D can cause its skew in two areas (zCx , zCy), as shown in fig. 3.

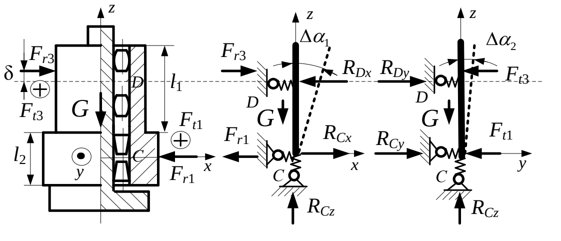


Fig. 4. Calculation scheme of the intermediate gear on elastic supports:
G – gear weight force; l 1, l 2 – the width of the gear sections; Δ α 1 Δ α 2 – skew angles

4. THE PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of this work is to study the functioning and character of wear of the teeth of the second stage of the intermediate gear of the gearbox of vertical rolls of "Slabing-1150" state.

To achieve the set goal, it is necessary to: investigate the statics of the intermediate gear of the gearbox with the influence of the type of supports and load; conduct an analysis of the nature of the wear of the working surfaces of the teeth of the intermediate gear after the regular year of operation; examine the hardness of the working and end surfaces of the teeth; develop recommendations for increasing the reliability of the intermediate gear.

4.1 Statics of the intermediate gear of the gearbox

1. The case when the gear supports are rigid; directions of forces F_{r3}, F_{t3} from R_{Dx}, R_{Dy} match the main assumptions of this formulation of the problem:

- misalignments of the leading and output gears;
- loads between gear teeth act in the middle of their lengths;
- bending deformations of the intermediate gear.

Solving the equations of statics for calculation schemes of the intermediate gear

(see Fig. 4) in the areas zCx, zCy gives the following expressions of reactions:

$$R_{Cx} = F_{r1};\ R_{Dx} = F_{r3};\ R_{Dy} = F_{t3};\ R_{Cy} = F_{t1} \quad (1)$$

However, the shafts of supports C and D in the radial direction (x or y) in reality are elastic and have different pliability:

(with Dx = with Dy) > (with Cx = with Cy), (2)

Which contributes to the formation of a misalignment of the intermediate gear at small angles Δ α 1 and Δα 2 respectively, in the areas zCx, zCy (Fig. 3). This contradicts assumption #2 and changes the expressions (1) of resistance reactions.

2. The case when a misalignment of the intermediate gear appears, and as a result, the appearance of load asymmetry relative to supports C and D - directions of forces F_{r3},F_{t3} do not coincide with R_{Dx}, R_{Dy}. Let's introduce the eccentricity δ of the action of the forces F_{t3}, F_{r3} (see Fig. 4). Taking into account the expressions for resistance reactions:

$$R_{Dx} = c_{Dx} \cdot (0{,}5l_1 + l_2) \cdot \Delta\alpha_1\ ;$$
$$R_{Dy} = c_{Dy} \cdot (0{,}5l_1 + l_2) \cdot \Delta\alpha_2; \quad (3)$$
$$R_{Cx} = c_{Cx} \cdot 0{,}5l_2 \cdot \Delta\alpha_1;$$
$$R_{Cy} = c_{Cy} \cdot 0{,}5l_2 \cdot \Delta\alpha_2. \quad (4)$$

Solving the equations of statics gives the following expressions for the gear misalignment angles:

$$\Delta\alpha_1 = \frac{F_{r3}\cdot(0{,}5l_2+0{,}5l_1+\delta)}{c_{Dx}\cdot(0{,}5l_1+0{,}5l_2)(l_1+L_2)} \quad 5)$$

$$\Delta\alpha_2 = \frac{2[F_{t1}\cdot l_2+F_{t3}(0{,}5l_2+0{,}5l_1+\delta)]}{c_{Dy}\cdot(0{,}5l_2+l_1)(l_1+L_2)} \quad (6)$$

where the value of δ can be determined by analyzing the nature of the most dangerous contact-fatigue wear of the working surfaces of the teeth.

4.2 Analysis of the nature of the wear of the working surfaces of the teeth of the intermediate gear

According to the literature review, the simplest visual method using hardness measurement was chosen for the analysis of the wear of the working surfaces of the intermediate gear teeth.

Analysis of the wear of the working surfaces of the teeth of the intermediate gear stage removed from operation after scheduled operation for one year. Considering that the tooth length is 450 mm, and the nature of the surface damage varies significantly in individual areas of the tooth, the inspection was carried out both in local areas, the dimensions of which were 15 ... 20 mm, and in relatively large areas with dimensions of 50 ... 120 mm. In addition, since the gear operates in the reverse mode, the inspection took into account the side of the tooth A and B, which conditionally correspond to the forward and reverse motion of the slab.

Fig. 5. Side A of the inspected gear tooth, length 450 mm

Fig. 5 shows the entire gear tooth from side A, and subsequent Fig. 6 show individual sections of the tooth 130…150 mm long. Inspection of these sections shows that the damage to the tooth surface varies significantly and cannot be represented as some one dominant type of damage.

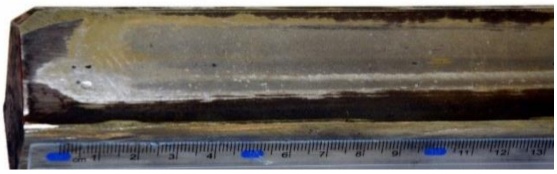
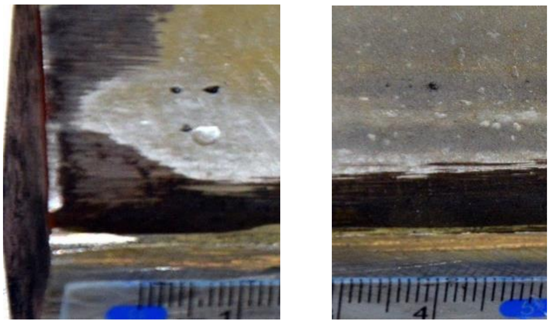


Fig. 6. Side A section from 0 to 140 mm

The analysis of the wear of the working surfaces of the teeth was carried out for the second stage of the intermediate gear, taken out of service after regular operation for one year. Since the gear works in reversible mode, the analysis was carried out for both sides of the teeth (their designations A and B) along the entire length (450 mm) with the selection of local zones (up to 150 mm).

The most characteristic photos of the teeth of the second stage of the intermediate gear of the gearbox are presented below vertical rolls of "Slabing-1150" condition.

Figure 8 (item a) shows a single deep fatigue shell and a group of small shells near it; in Fig. 9 (item b) – small fatigue shells; in fig. 9 (pos. c), the unloaded zone begins, where traces of grinding are visible.



a) b)

Fig. 7. The left half of the tooth (side A):
a – section 0...30 mm; b - section 30...60 mm
In fig. 5, and three shells and one plastic dent are shown; in fig. 5, b one large shell, two small shells and many small dents are observed.

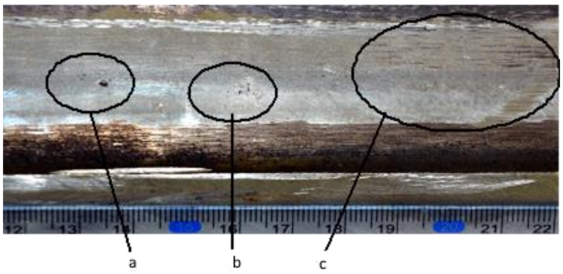


Fig. 8. Sections of the tooth with traces of chipping and dents (side A)

Fig. 9. A loaded section of a tooth with traces of burrs (side A)

Fig. 9 shows the entire gearbox tooth under study on side B. Even a superficial inspection of side B shows that it differs significantly from surface A both in the nature of the damage detected and in the location of its location.

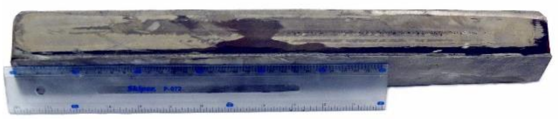


Fig. 10. Side B of the inspected gear tooth, length 450 mm

The figure shows that on the considered side of tooth B, 8 local zones can be distinguished, which differ significantly relative to the rest of the tooth surface. As characteristic damage, it is necessary to distinguish pronounced pitting, areas that perceive maximum loads, as well as zones that do not transmit torque at all.

The photos of side B shown below show a long pitting area, as well as local unloaded surface areas.

Fig. 11. A section of a tooth (130...220 mm) with traces of the beginning of cracking (side B)

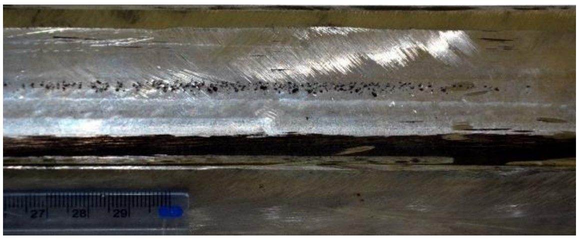


Fig. 12. Section of tooth (260...360 mm) with traces of continued chipping (side B)

Fig. 13. A section of a tooth (350...450 mm) with traces of the end of chipping (side B)

Contact-fatigue wear (see Fig. 11...13), as the most dangerous, characterizes the localization of the load on the second stage of the intermediate gear and makes it possible to determine the eccentricity of the forces F_{t3}, F_{r3} (δ = 80...90 mm).

The results of the investigation of contact fatigue damage of the intermediate gear by measuring the hardness of the working side and end surfaces according to the method described in [9] are presented, respectively, in fig. 11 and fig. 15.

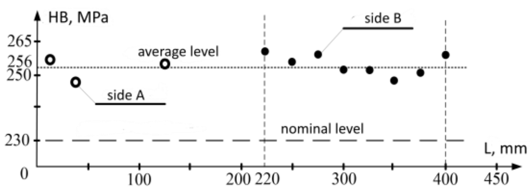


Fig. 14. Results of hardness measurements in pitting zones

Examination of contact-fatigue damage on the working side surfaces was carried out by measuring the hardness at the edges of the pitting holes, and on the previously finished end surfaces - at a distance of 0.5...1.0 mm from the edge of the involute profile in the zone of the radial transition of the tooth depressions. The nominal level of hardness (see Fig. 15) is defined as the average arithmetic value of the hardness on the side surface where there is no damage (see Fig. 9, item c). The average level of hardness (see Fig. 14) is defined as the average arithmetic value of the hardness on the side surface where contact fatigue damage is present (see Fig. 5, b - for side A; see Figs. 10...13 - for side B).

The results of hardness measurements in the dangerous zones of tooth depressions on the end surfaces are presented in fig. 15.

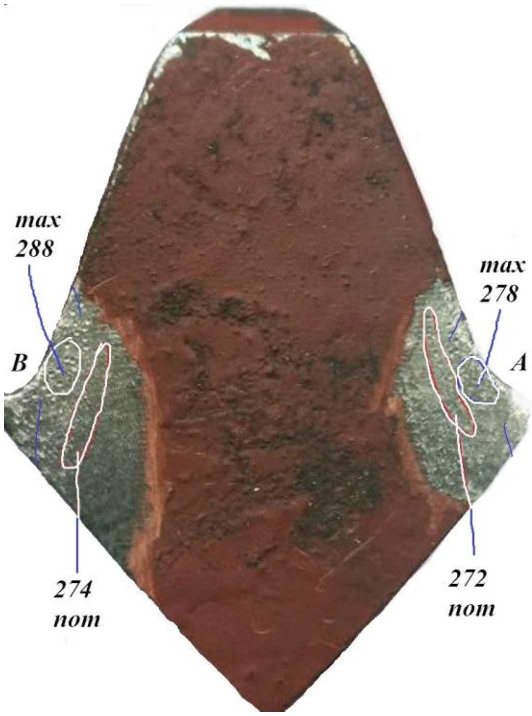


Fig. 15. Tooth end with measured hardness values

Average arithmetic nominal values of hardness (for 3 points at a distance of 5...7 mm from the profile of the tooth) of the end surfaces of the teeth on the A side showed HB nom A = 272 MPa, on the B side – HB nom B = 274 MPa; average maximum (for 3 points) on the side A – HB sr.ma x A = 278 MPa, on the B side – LV average x B = 288 MPa.

5. DISCUSSION OF RESEARCH RESULTS

The analysis of the wear of the working surfaces of the teeth of the intermediate gear of the reversible gearbox of the vertical rolls of the "Slabing-1150" rolling mill showed that the sides B, which correspond to the straight course of the slab, are more damaged. Several damages are observed on sides A in local areas: adhesive and contact-fatigue wear, plastic deformation. Some areas of the surfaces did not perceive the load at all, as they remained polished and undamaged.

Local single shells of cracks of large and small sizes on the surfaces of the tooth indicate the beginning of the process of contact-fatigue destruction, and plastic dents can be caused both by the insufficient quality of lubrication filtration and by random hard flakes that appeared during cleaning. The absence of traces of edge impact on the surfaces of the teeth indicates the efficiency of the flanking of the teeth.

The simultaneous presence of several of the above-mentioned types of damage indicates the need to perform strength calculations using a special methodology different from DSTU ISO 6336-2:2005, DSTU ISO 6336-3:2005. Taking into account the specific operating conditions of the intermediate gear will help to improve the quality of the design.

The presence of a long continuous zone (about 180 mm) of limited pitting, in contrast to single random pits, indicates the possibility of its transition after some time to the exfoliation zone. Therefore, the intermediate gear with such damage has almost completely exhausted its resource and can no longer remain in operation.

The possibility of monitoring the technical condition of gear wheels by the hardness of the working involute surfaces of the teeth in the pole zone and the end surfaces in the zone of the radial transition of the tooth depressions into the involute profile has been proven. An increase in hardness in these zones compared to the nominal hardness at a distance from the contact points and stress concentrators was established. Monitoring of gear wheels by material hardness can be used to develop a method for estimating the residual life of gear wheels.

The established cause of the misalignment of the intermediate gear of the gearbox indicates the need to improve the design of the unit by specifying the standard sizes of the supporting roller bearings and improving the design of the fixed shaft around which the gear rotates, with the aim of maximally reducing the angle of misalignment. The latter requires special studies of the statics and dynamics of the intermediate gear assembly.

6. CONCLUSIONS

Based on the results of the analysis of the statics of the intermediate gear of the reversible gearbox of the vertical rolls of the "Slyabing-1150" rolling mill, the reason for the misalignment of the gear was found. The expressions of the gear misalignment angles are defined, the result of which is the eccentricity of the forces of interaction of the second stage of the intermediate gear with the output gear.

The analysis of the nature of the wear of the working surfaces of the teeth of the intermediate gear revealed three types of damage: contact-fatigue and adhesive wear, plastic deformation. According to the most dangerous contact-fatigue wear after a year of operation, the eccentricity of the interaction forces in the engagement is determined. The sides of the gear corresponding to the straight course of the slab are more damaged.

To develop a method for estimating the residual resource of the gear, monitoring of the technical condition of the teeth of the intermediate gear by the hardness of the working involute surfaces in the pole zone and the end surfaces in the zone of the radial transition of the tooth depressions into the involute profile can be used.

To increase the reliability of the intermediate gear, it is necessary to carry out a set of theoretical and design measures. Theoretical research is necessary, firstly, to clarify the standard methods of calculating contact fatigue and bending fatigue in case of simultaneous presence of several types of damage, and secondly, to investigate the statics and dynamics of the intermediate gear unit. Design improvements of the gear unit should include specifying the selection of the standard sizes of the support shafts and making changes to the design of its stationary shaft.

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