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Method for predicting the remaining life of the ball mill support axle based on changes in the design stresses of the external surface of the axle

J A Bondarenko¹, T A Duyun^{2*} and O V Bestuzheva³

¹Professor of Department of mechanical engineering, BSTU named after V.G. Shukhov, Belgorod, Russia,

²Head of Department of mechanical engineering, BSTU named after V.G. Shukhov, Belgorod, Russia,

³Docent of the Department of applied informatics and information technologies, Belgorod National Research University, Belgorod, Russia,

E-mail: kdsm2002@mail.ru

Abstract. The article considers a method for predicting the residual life of the ball mill support axle based on changes in the calculated stresses of the external surface of the axle. The main terms of forecasting the remaining life of large-sized equipment are considered. The task is set and controlled parameters are selected for the development of the methodology. An algorithm for implementing a method for predicting the residual life of the ball mill support axle based on external surface stresses is presented. A method has been developed for predicting the residual life of ball mill support axles based on changes in the design stresses of the external surface of the trunnion, which allows you to set parameters that affect the duration of the residual life without stopping the mill and to adequately calculate the residual life of the trunnion, including from the start of operation of the mill. The homogeneity of the obtained data is estimated. The parameters of the stress distribution of the external surface of the trunnion are determined, indicating that the obtained distribution corresponds to the theoretical Weibull distribution and the validity of using this method for predicting the resource of the ball mill support trunnion. The values of the guaranteed residual life of the ball mill trunnion are calculated according to the developed method. The analytical dependence of the residual life of the ball mill trunnion on the equivalent stresses occurring on the external surface of the trunnion is given.

1. Introduction

In the production of cement, grinding equipment is the main link of the production line [1]. A significant dynamic impact of the load on the mill leads to a loss of performance, which contributes to long downtime in repairs. Increasing the productivity of equipment is achieved either by replacing it with a more productive one, or by increasing the reliability of the existing one [2].

According to GOST 27.003-2016 [3], the operational reliability of the object of continuous long-term use with the possibility of recovery and maintenance, which is the ball mill, is characterized by indicators of durability. Durability is the property of an object to maintain its functional state until the



limit state is reached with the installed maintenance and repair system, according to GOST 27.002-2015 [4].

According to table B. 2 of GOST 27.003-2016 [3], the indicator of durability for an object whose transition to the limit state when used for its intended purpose can lead to consequences, with the main process determining the transition to the limit state – wear and aging simultaneously, is the average and gamma percent (guaranteed) residual resource and the average and gamma percent (guaranteed) service life. To assess the durability from the selected reference point to the onset of the limit state of the equipment, use the average and gamma percent (guaranteed) residual life.

The residual resource is the total operating time of object from the time of control of its technical condition up to the moment of reaching the limit state, with average life – expectation of the resource to a guaranteed resource is the total time during which the object reaches a limiting state with probability, expressed in percentage according to GOST 27.002–2015 [4].

Operational failures of equipment are manifested in changes in the parameters of the technical condition of the directly measured values of damage or output parameters of the equipment [4]. Their monitoring allows you to predict the moment when hardware failure occurs. According to GOST 27.002-89 [4], a failure is an event that results in a violation of the object's functional state. The technical condition of a ball mill, in which its further operation or restoration is impractical or unacceptable, is its limit state [3]. Restoration of worn-out equipment due to technical and economic indicators or violations of established safety requirements, according to GD 09-10-95 and GOST R 22.2.05-94 [5, 6], is impractical.

The limit state of the equipment, according to GOST 27.002-89 [4], is characterized by the criteria of the limit state. When providing operational and technical parameters, the operating time from monitoring the technical condition of the ball mill or its repair, the average gamma percentage and residual resource is an indicator of durability.

The complex stress-strain state of the ball mill support axle determines the dependence of stresses and deformations on the temperatures of the internal and external surface of the axle [7]. To determine deformations, measurements of deviations in the nominal diameter of the external surface of the trunnion are required. Based on the obtained data, it is possible to estimate the residual life of the ball mill trunnion by changing the output parameters, according to GD 26.260.004–91 [6].

The task is to develop a methodology for predicting the remaining life of the trunnion, which will allow you to adequately calculate the remaining life of the trunnion without stopping the mill, including from the beginning of its operation, and to establish parameters that affect its duration. The controlled parameter for the development of the method is the stress of the external surface of the trunnion, which occurs under the influence of gravity, rotation and temperature field.

2. Materials and methods

The algorithm for implementing the method for predicting the residual life of the ball mill support pin by external surface stresses is shown in figure 1. the Method for predicting the residual life of the pin by changing the controlled parameter-voltage includes the following steps:

1. Getting initial data: the temperature of the external surface of the unloading pin and the temperature of the material coming out of the mill.
2. Determination of surface areas for calculating the stresses of the external surface of the ball mill trunnion.
3. Calculation of equivalent stresses of the external surface of the ball mill trunnion by sections, according.
4. Statistical processing of the received data:

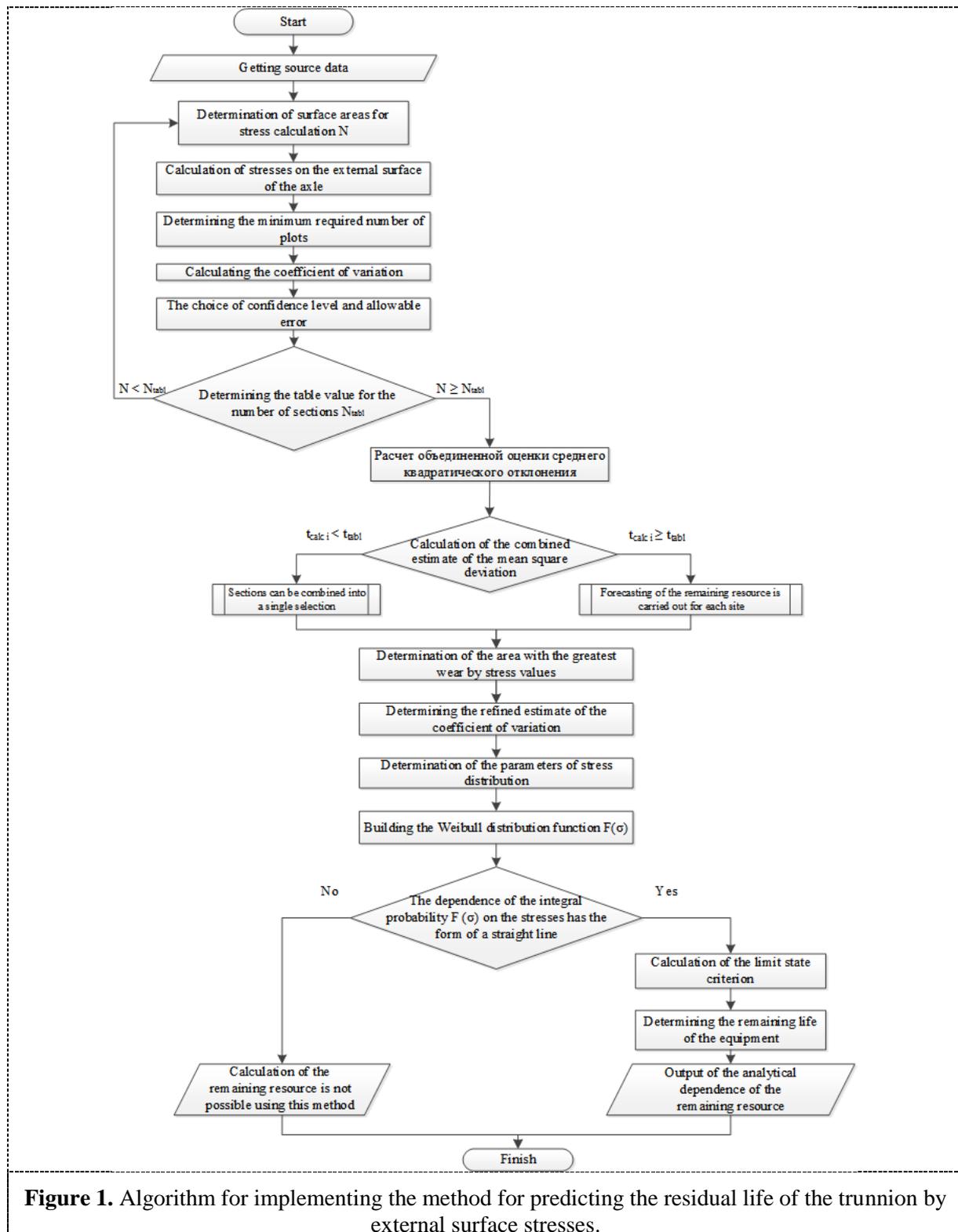


Figure 1. Algorithm for implementing the method for predicting the residual life of the trunnion by external surface stresses.

- 4.1. Determination of the minimum required number of plots for calculation:
 - 4.1.1. Calculation of average values, average square deviation and coefficient of variation.
 - 4.1.2. Selecting the confidence probability and maximum permissible relative error.
 - 4.1.3. Comparison of the selected number of plots with the table value.

- 4.2. Assessment of the homogeneity of the obtained sample:
 - 4.2.1. Calculation of the combined estimate of the mean square deviation.
 - 4.2.2. Determining the calculated value of the student's criterion.
 - 4.2.3. Comparison of the calculated and tabular values of the student's criterion.
 - 4.2.4. Conclusion about the homogeneity of the sample and the possibility of combining the sample sections.
- 4.3. Check the sound application of the technique of forecasting of a residual resource of axle:
 - 4.3.1. The choice of the site of greatest wear on the outer surface of the axle.
 - 4.3.2. Determination of a refined estimate of the coefficient of variation for the area of greatest wear.
 - 4.3.3. Selection of distribution parameters based on the updated estimation of the coefficient of variation.
 - 4.3.4. Output of the Weibull probability distribution function with the construction of a dependency graph and its data to determine the reliability of the developed method.
5. Predicting the remaining life of the ball mill support axle:
 - 5.1. Formulation of the criterion for the limit state of the ball mill axle.
 - 5.2. Determination of the average wear rate and coefficient of variation of the resource.
 - 5.3. Finding the average and guaranteed residual life of the ball mill trunnion.
6. Conclusion of the analytical dependence of the residual resource on the equivalent stresses occurring on the external surface of the trunnion.

A change in the technical condition parameter-the stresses that occur on the outer surface of the trunnion, indicates uneven wear [8], explained by the stochastic property of the system: temperature, composition, speed, and concentration of material particles [9].

3. Results

According to figures [7], the stresses on the outer surface of the ball mill pin change as the temperature of the inner surface increases. At the same time, it was found that the highest stress values are reached on the external surface of the unloading pin. Therefore, let's consider the method of predicting the residual life of the unloading trunnion on the example of a ball mill with a standard size with diameter of 3.2×15 m.

1. Determine the surface areas for calculating the stresses on the outer surface of the ball mill trunnion. It is impractical to estimate the degree of wear of the ball mill trunnion along the length of the working cylindrical surface for all sections under the same conditions. Selected 6 sections for determining the stress (figure 2). It is required to perform calculations on the sections of the external surface of the trunnion.

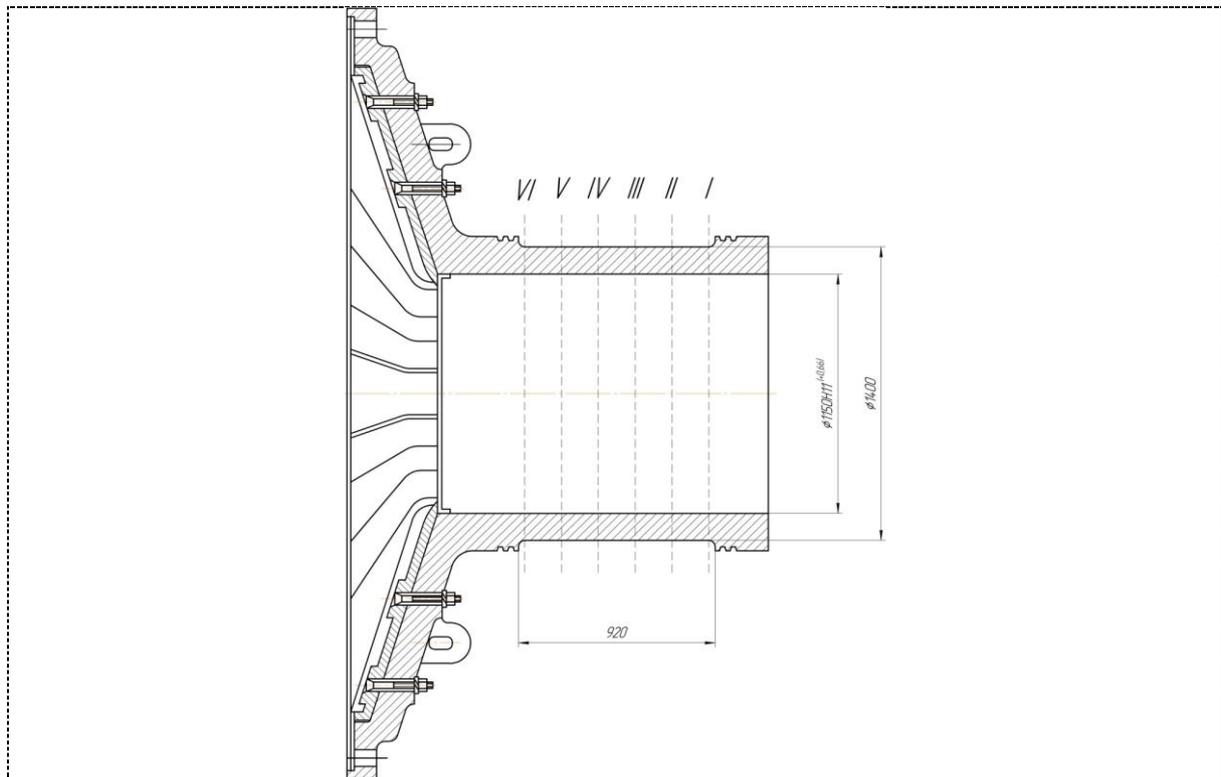


Figure 2. Layout of sections for calculating the stress on the surface of the trunnion.

Figure 2 shows the layout of the sections for calculating the stress on the surface of the trunnion.

2. Calculate the stresses on the outer surface of the trunnion at an average constant temperature of the outer surface of the unloading trunnion $T_{R_2} = 58^\circ\text{C}$ [7], varying the values of the inner surface temperature. The characteristics of the calculated stresses on the external surface of the trunnion are shown in table 1.

3. Produce statistical processing of the obtained data.

3.1. Determine the minimum required amount of sample size.

To do this, calculate the statistical characteristics: the average value of the external surface stress on the site, the average square deviation and the coefficient of variation (table 1). Table 1 shows and calculates the following characteristics:

- T_{R_1} – change in the temperature of the inner surface of the axle, $^\circ\text{C}$;
- σ_i – calculated value of the equivalent voltage on the section, MPa;
- $\bar{\sigma}_i$ – average value of equivalent stresses on the i-th section, MPa:

$$\bar{\sigma}_i = \frac{\sum_{i=1}^n \sigma_i}{n}; \quad (1)$$

- S_i – mean square deviation on the I-th section, determined by the formula, according to [10]:

$$S_i = \sqrt{\frac{\sum(\sigma_i - \bar{\sigma}_i)^2}{n_i - 1} - \left(\frac{\Delta}{3}\right)^2}, \quad (2)$$

where Δ – limit error of the method when determining the residual life of equipment by voltage;

- V_i – coefficient of variation on the i -th section, according to [10]:

$$V_i = \frac{S_i}{\bar{\sigma}_i}, \quad (3)$$

Table 1. Characteristics of the calculated voltages.

№ section	$T_{R_1}, ^\circ\text{C}$	σ_i, MPa	$\bar{\sigma}_i, \text{MPa}$	S_i	V_i
I	115	137.33	143.10	4.9761	0.0348
	116	139.73			
	117	142.14			
	119	146.95			
	120	149.35			
II	121	151.76	158.01	4.9761	0.0315
	122	154.16			
	124	158.97			
	125	161.37			
	126	163.78			
III	127	166.18	173.40	5.3674	0.0310
	129	170.99			
	130	173.40			
	131	175.80			
	133	180.61			
IV	134	183.02	189.75	5.7320	0.0302
	135	185.42			
	137	190.23			
	138	192.63			
	140	197.44			
V	140	197.44	202.73	3.5524	0.0175
	142	202.25			
	142	202.25			
	143	204.66			
	144	207.06			
VI	145	209.47	214.27	5.0909	0.0238
	145	209.47			
	147	214.27			
	148	216.68			
	150	221.49			

3. To select the required minimum number of plots for N_{tabl} calculations, you need to determine the values of confidence probability and acceptable error. Accept the confidence probability of the estimation, according to [11]:

$$\Delta = 0.95; \quad (4)$$

4. and the maximum permissible relative error, according to [11]:

$$D = 0.10. \quad (5)$$

5. The calculated coefficients of variation (table 1) do not exceed the value of 0.1. According to table 4 [12], for the given values (4) – (5), we find the minimum:

6. $N_{\text{tabl}} = 5$,

7. this confirms the validity of the selected number of sections, equal to $N = 6$.

8. 3.2. Perform an estimation of the homogeneity of the obtained data. Since different areas of the ball mill shaft surface experience different intensity of stress influence during operation [7], it is necessary to check the obtained data for uniformity. Checking the uniformity of the data obtained by the student's criterion of adjacent sections of the axle surface using the formula, according to [12]:

$$t = \frac{|\bar{\sigma}_i - \bar{\sigma}_{i+1}|}{S \sqrt{\frac{1}{n_i} + \frac{1}{n_{i+1}}}} < t_T, \quad (6)$$

9. where $\bar{\sigma}_i, \bar{\sigma}_{i+1}$ – mean value of the voltage at the i -th and $(i+1)$ -th portions of the surface; n_i, n_{i+1} – number of measurements on adjacent areas; S – joint estimation of mean-square deviation, calculated according to the formula [11]:

$$S = \sqrt{\frac{S_i^2(n_i-1) + S_{i+1}^2(n_{i+1}-1)}{n_i + n_{i+1} - 2}}, \quad (7)$$

10. where S_i, S_{i+1} – RMS deviation at the i -th and $(i+1)$ -th sections, defined by the formula (2) (table 1);

11. t_T – tabular value of the student's criterion for the calculated number of degrees of freedom (8) and significance level (3.4).

12. The number of degrees of freedom, according to [10], is determined by the formula:

$$f = n_i + n_{i+1} - 2 = 8. \quad (8)$$

13. Let's calculate the values of the combined estimate of the mean square deviation for the sample sections and the student's criteria. The calculation results are shown in table 2.

14. Since condition (6) is met on all surface areas, the stress differences are not statistically significant and the calculation results can be combined, which will improve the accuracy of predicting the remaining life [12]. Thus, it is proved that the resource can be determined for the entire external surface of the trunnion by the values of the area of greatest wear [6].

15. 3.3. The reasonable application of the method of forecasting the residual life of the ball mill trunnion is verified. According to tables 1-2, the area of the greatest wear of the external surface is the VI section.

16.

Table 2. Assessment of the homogeneity data.

Sections	Statistical characteristic				Comparison with a table $t_T = 2.306$	
	σ_i, MPa	S_i	S	t		
I – II	I	143.10	4.9761	4.9761	1.8948	$t < t_T$
	II	158.01	4.9761			
II – III	III	173.40	5.3674	5.1754	1.8806	$t < t_T$
	IV	189.75	5.7320			
III – IV	V	202.73	3.5524	4.7684	1.7222	$t < t_T$
	VI	214.27	5.0909			

17. A refined estimate of the stress variation coefficient was determined [11]:

$$V_\sigma = \sqrt{\frac{\sum_{i=1}^N V_i^2 \cdot n_i}{N}}, \quad (9)$$

18. where $V_{\sigma i}$ – coefficient of variation on the surface area of the greatest wear; n_i – number of measurements on this area; N – number of surface areas.

19. Then

$$V_\sigma = 0.0642. \quad (10)$$

20. 4. To describe failures caused by wear on the part surface, we will use the Weibull distribution function [13], which has flexibility in approximating the distribution and is widely used in the practical implementation of the reliability theory [14].

21. The distribution function is assumed in the form, according to [15]:

$$F(\sigma) = 1 - e^{-\left(\frac{\sigma_i}{a}\right)^b}, \quad (11)$$

22. where σ_i – equivalent stresses of the external surface of the axle; a - parameter of the distribution scale, determined by the formula, according to [16]:

$$a = \frac{\sigma_{\text{imax}}}{k_v}, \quad (12)$$

23. where k_v is the coefficient that depends on the coefficient of variation;

24. b – parameter of the distribution form, determined by the coefficient of variation.

25. For the calculated refined estimation of the stress variation coefficient (10), it is necessary to determine the values of the distribution parameters.

26. Distribution parameter values defined according to [17]:

$$k_v = 0,887; a = 274,5; b = 3,6; \gamma = 0,05. \quad (13)$$

27. According to the calculated values (13), the voltage distribution function (11) takes the form:

$$F(\sigma) = 1 - e^{-\left(\frac{\sigma}{274,5}\right)^{3,6}}. \quad (14)$$

28. The results of statistical processing were plotted on Weibull's probability paper (figure 3).

29.

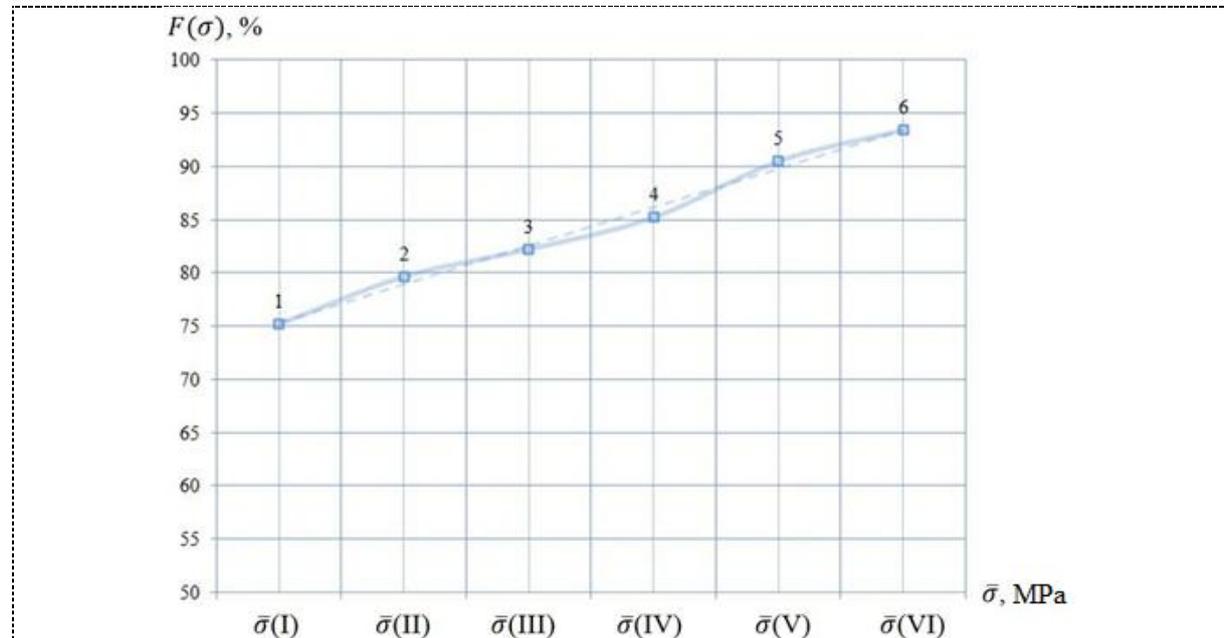


Figure 3. Stress distribution on the Weibull probability paper: 1 – probability $F(\sigma) = 75,1\%$ at $\bar{\sigma} = 214,27$ MPa; 2 – probability $F(\sigma) = 79,5\%$ at $\bar{\sigma} = 202,73$ MPa; 3 – probability $F(\sigma) = 82,4\%$ at $\bar{\sigma} = 189,75$ MPa; 4 probability $F(\sigma) = 85,1\%$ at $\bar{\sigma} = 173,4$ MPa; 5 – probability $F(\sigma) = 91,3\%$ at $\bar{\sigma} = 158,01$ MPa; 6 – probability $F(\sigma) = 93,5\%$ at $\bar{\sigma} = 143,1$ MPa.

30. The stress distribution graph indicates the probability of average stress values as a percentage: a decrease in stress leads to an increase in the distribution function (figure 3). In the graph shown in figure 3, the points are approximated in a single line, which corresponds to the obtained theoretical Weibull distribution and indicates the validity of using this technique to predict the resource of the ball mill trunnion.

31. 5. Determine the residual resource of the ball mill axle. To predict the remaining life, it is necessary to formulate a criterion for the limit state of the ball mill trunnion. The strength criterion for a complex stress-strain state of the ball mill trunnion with a standard size with diameter of 3.2×15 m, made of a material – 35L steel, is determined according to [18]:

$$\sigma_i < 490 \text{ MPa}. \quad (15)$$

32. Given [19], expression (15) will have the form:

$$\sigma_z + \frac{\tau-1}{\sigma-1} \sigma_\varphi < 490 \text{ МПа}, \quad (16)$$

33. To determine the average and guaranteed residual life, find the average wear rate and the coefficient of variation of the resource.

34. The average wear rate is determined by the formula:

$$c = \frac{\alpha}{\tau} = \frac{274,5}{4} = 68,61 \text{ МПа/г}, \quad (17)$$

35. where τ – average time to failure in years, according to [20].

36. The calculated average life of the ball mill trunnion is determined according to [6]:

$$T_p = \frac{\sigma_B \cdot k_V}{c \cdot (-\ln \gamma)^b} = \frac{490 \cdot 0,887}{68,61 \cdot (-\ln 0,05)^{3,6}} = 4,67 \text{ years}. \quad (18)$$

37. To determine the guaranteed resource, we calculate the coefficient of variation of the resource, according to [12]:

$$V_T = \frac{V_\sigma}{\sqrt{\sum_{i=1}^N n_i}} = \frac{0,0642}{\sqrt{30}} = 0,011. \quad (19)$$

38. The guaranteed (gamma-percent) resource is determined by the formula, according to [6]:

$$T_\gamma = T_p (1 - u_\gamma V_T), \quad (20)$$

39. where u_γ – quantile of the normal distribution with the level $\gamma = 0.05$: $u_\gamma = 1.645$.

40. Thus, the value of the guaranteed residual life of the ball mill axle is calculated:

$$T_\gamma = 4.59 \text{ years}. \quad (21)$$

41. 6. Conclusion of the analytical dependence of the residual resource on the equivalent stresses occurring on the external surface of the trunnion.

42. A thorough technical diagnostics is required to assess the remaining service life of a ball mill depending on the complex stress-strain state of the trunnion. For diagnostics, devices are used that control the metal surface and determine the distribution and intensity of certain interference bands, which visually determine the concentration of mechanical damage, but the direction and values of deformations and stresses are ignored [21]. This method does not provide a complete assessment of the stress-strain state of the surface.

43. Complex stress-strain state of the axle considered in the second Chapter, involves the wear of the sliding surface, depending on many factors: accuracy of selection of materials of the bearing and the axle that the contact points of the insert bearing and axle, observance of technological process of recovery, compliance with performance standards, timeliness of diagnostics and preventive maintenance [22].

44. In view of the complexity of estimating the remaining life and the impossibility of conducting field tests to determine the durability of the operating equipment, depending on the above factors, it is of interest to predict the durability.

45. Tests of samples at various constant deformation rates [23] indicate that the influence of the duration of loading on the mechanical strength of parts is conditioned. In the course of durability studies conducted by many scientists [24, 22, 25], experimental and theoretical results have been obtained, which are the fundamental basis for the development of the kinetic concept of solid strength, which is currently generally recognized.

46. Wear is considered as an irreversible temporary process in the deformable volume of structural damage to the surface of the material. The destruction process occurs when the critical level of damage is reached, according to (15) [22].

47. Quantitative measure of damage is considered a partial gap corresponding to the relative duration of the voltage to the longevity of details in this load:

$$\sum_{i=1}^k \frac{t_i}{\tau_i(\sigma_i)} = 1, \quad (22)$$

48. where t_i – the time of action of the tension; $\tau_i(\sigma_i)$ – durability parts for a given load.

49. If the voltage is determined by a continuous function of time, then the Bailey criterion is implemented instead of the condition (3.21) [25]:

$$\int_0^{\tau} \frac{dt}{\tau[\sigma(t)]} = 1, \quad (23)$$

50. which allows us to establish the time dependence of the strength for a given loading mode for an analytically defined function $\tau[\sigma(t)]$ for $\sigma(t) = \sigma = \text{const}$.

51. The linear law of damage accumulation in the form of equations (22) and (23) is approximate [23, 26] and is valid only under relatively unchanged material structure, that is, under conditions of brittle destruction in the absence of shape change. Nonlinear laws are more universal.

52. According to [25], the time dependence of the material strength under dynamic conditions is described by an exponent in terms of the ratio of the equivalent stress to the maximum allowable stress value in logarithmic coordinates [26].

53. In accordance with the biki criterion [27], the analytical dependence of the residual resource [30] is obtained:

$$T = \alpha \cdot e^{-\left(\frac{\sigma}{\sigma_s}\right)^{\gamma}}, \quad (24)$$

54. where α – the material parameter that depends on external temperature factors (coefficient of linear expansion, deg.⁻¹); σ_s – the material strength limit, MPa; σ – the stresses arising during operation of the trunnion, MPa; γ – the level of significance, according to (13).

55. Substituting the numerical values σ_s and γ , the dependence (24) will have the form:

$$T = \alpha \cdot e^{\left(\frac{\sigma}{490}\right)^{0,05}}. \quad (25)$$

56. Substituting the range of stress values and the value of the linear expansion coefficient, we construct a graphical dependence of the residual resource on the equivalent stresses that occur on the external surface of the trunnion (figure 4).

57.

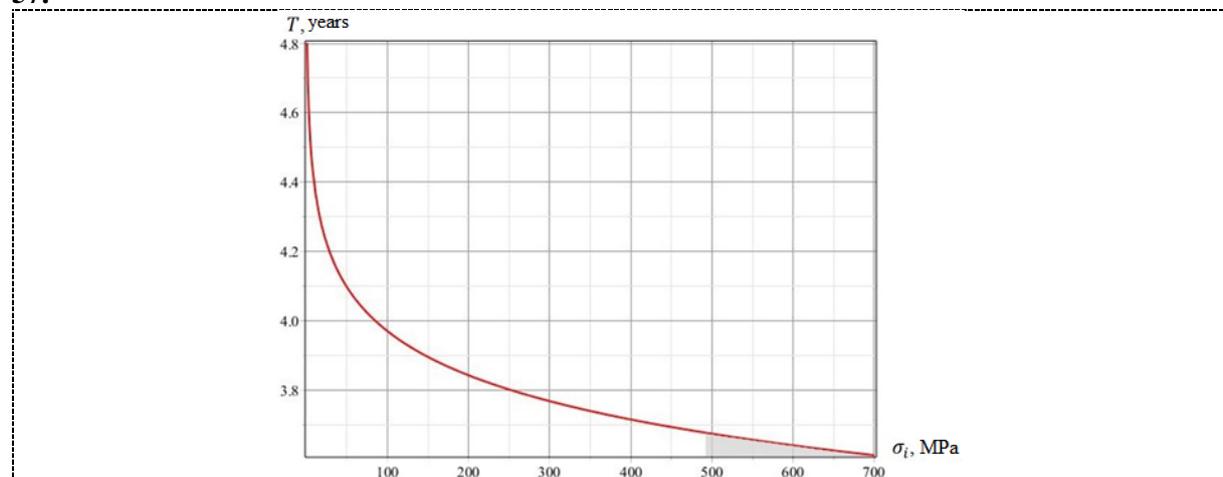


Figure 4. Graph of the dependence of the residual life of the ball mill trunnion on the equivalent stresses occurring on the external surface of the trunnion.

58. As follows from figure 4, the dependence has a monotonously decreasing character – with an increase in equivalent stresses, the residual resource decreases accordingly. The area of invalid values is highlighted in color on the graph, according to the limit state criterion (4).

59. 3. Results and discussions

60. Using a mathematical description and known analytical expressions, a method for predicting the residual life of ball mill support axles based on changes in the calculated stresses of the external surface of the trunnion is developed. The method allows you to set parameters that affect the duration of the residual life without stopping the mill and to adequately calculate the residual life of the trunnion, including from the start of operation of the mill. The homogeneity of the obtained data is estimated:

61. The parameters of the stress distribution of the external surface of the trunnion are determined, indicating that the obtained distribution corresponds to the theoretical Weibull distribution and the validity of using this method for predicting the resource of the ball mill support trunnion.

62. The values of the guaranteed residual resource of the ball mill trunnion are calculated according to the developed method: the average residual resource is $T_p = 4.67$ years, the guaranteed resource is $T_{py} = 4.59$ years.

63. The analytical dependence of the residual life of the ball mill trunnion on the equivalent stresses occurring on the external surface of the trunnion is given.

4. Summary

Using a numerical method for a mill size with diameter of 3.2×15 m, the analysis of the dependence of stresses and deformations occurring on the external surface of the trunnion on the temperature difference of its internal and external surfaces was carried out. It was found that with an increase in the temperature difference in $\Delta T_R = 120^\circ\text{C}$ ($T_{R_1} = 157^\circ\text{C}$, $T_{R_2} = 37^\circ\text{C}$), the stresses in both the circumferential and axial directions grow and amount to $\sigma_\varphi = \sigma_z = 172$ MPa, the deformations in the circumferential and axial directions monotonously increase and reach $\varepsilon_\varphi = 4.6$ mm, $\varepsilon_z = 5.8$ mm. The maximum strain value in the radial direction is $\varepsilon_r = 4.102$ mm. The unloading axle is subject to a more complex stress-strain state under the influence of a temperature field, and the external surface of the axle has the highest values of stresses and deformations.

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