***Виявлений механізм змішаного руйнування валків, що призводить до поступового зростання дефектів від поверхневих пошкоджуючих процесів. Встановлена послідовність змін напружень у небезпечних зонах валка за один його оберт. Розроблений алгоритм прогнозування періоду живучості, заснований на лінійній моделі зростання дефекту. Проблеми дії різноманітного механізму руйнування та нестаціонарності навантаження валків вирішуються методом кривих живучості***

***Ключові слова: листопрокатний валок, діагностування роботоспроможності валка, поверхневий дефект металу, технічне обслуговування прокатного стану***

***Выявлен механизм смешанного разрушения валков, приводящий к постепенному росту дефектов от поверхностных повреждающих процессов. Установлена последовательность изменения напряжений в опасных зонах валка за один его оборот. Разработан алгоритм прогнозирования периода живучести, основанный на линейной модели роста дефекта. Проблемы действия смешанного механизма разрушения и нестационарности нагружения валков решаются методом кривых живучести***

***Ключевые слова: листопрокатный валок, диагностирование работоспособности валка, поверхностный дефект металла, техническое обслуживание прокатного стана***

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# PREDICTION OF OPERABILITY OF THE PLATE ROLLING ROLLS BASED ON THE MIXED FRACTURE MECHANISM

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## 1. Introduction

Rolls, as tools for mass production of metal rolled products, have always been in the sphere of special interest of technologists and mechanical engineers of the metallurgical industry. When the rolls become fitting technological regulations, the issues of their durability come to the forefront. According to the classifier of the main means of production, rolls of plate and plate-rolling mills are the most expensive and belong to the 3rd depreciation group (3 to 5 years of useful operation for work rolls) and to the 4th depreciation group (5 to 7 years of useful operation for back-up rolls) [1]. Such life times are adopted by designers to ensure structural strength reserves of the roll body for the required durability taking into account the specified number of roll redressings that is checked for contact pressures.

The roll stock services organized at metallurgical enterprises are exclusively responsible for condition and repair of the rolls. The failure analysis conducted at four continuous plate-rolling mills has shown that about a third of the failures occurring in the working cages and main lines are caused by roll breakage. In general, work rolls break most and breakage of back-up rolls occurs rarely [2].

Some rolls can weigh tens of tons and cost several hundred thousand euros. It is clear that roll failure has a negative impact on the production economy. This necessitates removal of rolls from service after reaching the normative number of redressings and the minimum diameter of the working section. On the other hand, given availability of the shop roll stock numbering dozens of sets, premature (before exhausting the service life) discarding the rolls for scrap also significantly increases rolling cost. Management of the majority of metallurgical enterprises sets reduction of roll consumption as one of the urgent problems solved in various ways. But to that end, it is necessary first of all to reliably predict technical condition and residual life of the rolls.

In order to have this opportunity in production, an appropriate information base on the roll characteristics and its initial life should be prepared at the design and fabrication stages. This requires development of the models of degradation processes even in more details than it is made in calculation of strength margin. From the point of view of reliability, the roll has features of a complex technical system since it is affected by a number of damaging processes. In this case, not all of them result directly in the loss of operability but each of them worsens roll condition degrading quality of the rolled product. The roll operability is connected with volumetric phenomena: its complete breakage or delamination of large pieces of metal because of depth fatigue. The danger of these phenomena is exacerbated by the absence of visual diagnostics signs. Surface phenomena (tribological, thermal) are successfully, though troublesome, revealed in operation. Using the notions of technical diagnostics, one can consider that the roll operability is supported by maintenance proceeding from their technical condition. However, in general, rolls are operated either up to the normative life or to their failure (breakage). They are rarely operated to the pre-failure state envisaged by the proactive service strategy. Thus, the strategy of maintenance and repair of rolls does not match the strategy of their use. This is explained by complexity of diagnosing working states and the obviousness of diagnosis of operable conditions. As a result, it is impossible to estimate the degree of life depletion of the roll itself (not its surface).

## 2. Literature review and problem statement

The studies of roll durability carried out by rolling process engineers conventionally prevail in literature. A posteriori models of the rolls service life are obtained in them by the methods of mathematical statistics applicable for prediction of the mill roll life as the object of studies [3–5]. There is a need for a priori models of operability based on probabilistic-physical reliability methods.

Studying the nature of roll failure, specialists came to the conclusion that the processes of interaction of work rolls with metal and back-up rolls play an important role in the problem of durability. Along with the region of adhesion, there is a slipping region in the contact zone in which fretting processes occur where start and propagation of failure occurs in the *II* mode (transverse shear) [6]. It was established that the threshold value of SIF for steels with $\Delta K_{thII}$=3...6 MPa·m$^{0.5}$, which is 1.5...3 times smaller than the threshold value of SIF for the *I* mode of failure (normal breakaway) [7, 8]. When the rolls contact with each other, alternating tangential (reverse) stresses amounting hundreds of MPa appear in their subsurface layers. Since these stresses vary cyclically within the surface contact area, presence of a discontinuity of one hundredth of millimeter or several structural units of material is sufficient to initiate failure [6]. For such huge parts as the rolling mill rolls, this means that failure starts practically from the beginning of operation. Reverse stresses are responsible for appearance of internal cracks which cause delamination of metal pieces from the roll (spalling), a common type of failure of rolls in finishing stands [8]. Presence of tangential friction forces in the contact areas leads to movement of tangential stresses from the depth to the surface. This is especially pronounced when the rolling process is violated with formation of strip folding (cobbling) [9]. As a result, sagittal cracks appear and propagate obliquely from the surface into the depth of the roll body [10]. Cracks of the *II* mode resulting from contact fatigue cannot bring about roll breakage since SIF decreases with their growth. At some metallurgical plants, presence of surface cracks is not considered a defect. Further development of such cracks requires additional conditions with new failure mechanisms. For example, roll spalling (pitting) is associated with development of a sagittal crack by the *I* mode because of its hydraulic wedging with the roll lubricating and cooling liquid [10]. Under specific conditions of deformation of a real part, various scenarios of alternation of failure mechanisms are possible which results in a subsequent stage of the roll life [6]. This work is devoted to revealing the mechanisms of final roll breakage after development of the defects brought about by surface phenomena.

Thus, early crack formation makes it expedient to construct diagnostic models of rolls based on the methods of fracture mechanics [11]. Similar models were used since the 1970s for the designed ‘5000’ plate-rolling mill [12]. Strength criteria of brittle fracture are widely used to substantiate what is the ultimate size of defects in the roll body [13]. The period of development of a crack-like defect is considered only for surface phenomena that initiate volumetric destruction [14]. Particular attention is paid to studying the processes of roll spalling occurring in rolling shops. In particular, the processes of thermal cycling can cause appearance of subsurface cracks in plate-rolling work rolls [15]. Also, development of small cracks into propagating cracks is of interest [16]. Most often, contact fatigue is the cause of appearance of surface cracks in plate-rolling back-up rolls [17]. However, insufficient attention is paid to prediction of the roll life based on the data of ultimate roll failure.

## 3. The aim and objectives of the study

This study objective was to work out a diagnostic algorithm for assessing technical condition of the plate rolling rolls and predicting the remaining roll life.

To achieve this objective, the following tasks were set:

– consider the character and evaluate probability of defect formation in the roll metal during rolling under the influence of internal force factors on the roll durability in conditions of cyclic loading;

– establish sequence of action of the destruction mechanisms and stresses at the stage of defect development;

– develop an algorithm for determining survivability of rolls and test its effectiveness for a continuous plate-rolling mill.

## 4. Evaluation of survivability of the rolling mill roll

### 4. 1. Internal force factors of the roll during rolling

The roll is a short beam working under conditions of transverse bending. The action of transverse forces leads to formation of tangential stresses which can be estimated in engineering practice from the shear stress:

$$\tau_{\mathrm{sh}} = \frac{P}{2 \cdot A}, \quad (1)$$

where *P* is the rolling force; *A* is the cross-sectional area.

Tangential torsion stresses are determined as:

$$\tau_{\mathrm{tr}} = \frac{M}{0{,}2 \cdot D^3}, \quad (2)$$

where *M* is the moment of rolling:

$$M = P \cdot h.$$

For the roll (Fig. 1), relationships between tangential stresses induced by the moment and the force of rolling and the normal bending strains σ brought about by the rolling force look like this:

$$\tau_{sh} / \sigma = 1/8\gamma_{lb}, \tag{3}$$

$$\tau_{sh} / \tau_{tr} = 1/8\gamma_{lh}, \tag{4}$$

where $\gamma_{lb}=L/D$, $\gamma_{lh}=h/D$ are the arm coefficients for bending and torsion, respectively.

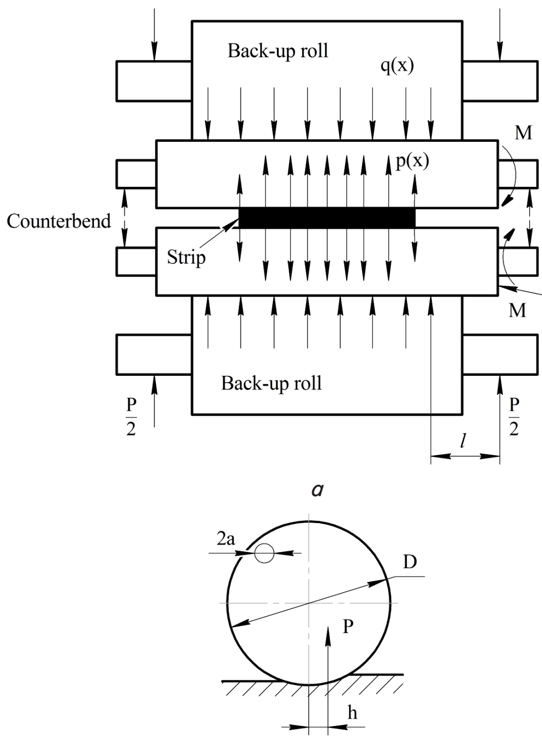
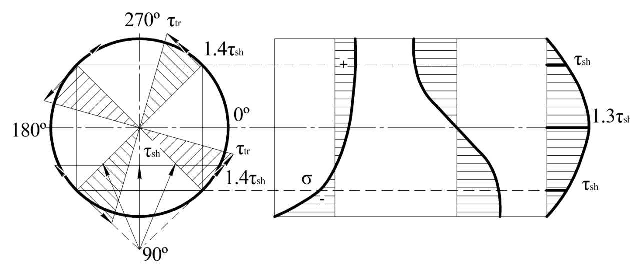



Fig. 1. Strip rolling in cages of quarto type: the diagram of loading of the work roll and the back-up roll by distributed forces $p(x)$ and $q(x)$ from the rolling force $P$ and the bending force (*a*); diagram of location of a spherical defect in the surface layer of the roll (*b*)

Taking into account that $\gamma_{lb}<1$ and $\gamma_{lh}<<1$ for plate rolling rolls, the tangential stresses $\tau_{sh}$ are comparable with the bending stresses σ and exceed the torsional stresses $\tau_{tr}$. Since the stress $\tau_{tr}$ is taken into account when calculating rolls for strength margin, it makes no sense not to take into account stresses $\tau_{sh}$, especially since the frequency of changes in the stresses $\tau_{sh}$ is much higher than for the stresses $\tau_{tr}$ (Fig. 2, *a*). It corresponds to the frequency of revolution of the rolls. The frequency of variation of torsional stresses is determined, first of all, by the period of exit of the rolled strip from the rolls. Consequently, intensity of accumulation of fatigue damages from the stresses $\tau_{sh}$ should be higher.

This applies not only to the roll barrel where the surface degradation processes are active. As a rule, normal stresses in the roll necks are insignificant and it is difficult to explain fractures in these zones with the help of the conventionally used model of the roll strength in a form of resistance to the joint action of bending and torsion. But it is condition of the necks that largely determines full life of the roll before its discarding since it is difficult to restore rolls by repairs. Defects here appear because of the action of the cooling liquid and have a corrosive origin.

Sulfides entering the roll surface significantly reduce its fatigue strength [18].




*a* *b* *c* *d*

Fig. 2. Stressed state of the roll: distribution of tangential stresses in the cross section (*a*); distribution of normal stresses in the longitudinal section; deformation of the cross section along the roll length (*c*); distribution of tangential stresses in the longitudinal section (*d*)

In addition, the desire of process engineers to improve flatness of the rolled products thru stiffening the stands prompts the use of multi-row bearings in the roll supports the gaps in which disappear at relatively low rolling forces and the roll is deformed as a fixed beam. As a result, under the bearings, the roll is subjected to an additional fatigue process from bending and rotation with the amplitude equal to the bending moment in the roll barrel. Since the diameter of necks is less than that of the barrels, stresses and damages are higher there. This confirms relevance of studying the effect of fracture of a mixed nature on the roll life.

A number of features that most clearly manifest themselves in prismatic specimens were discovered by the authors when testing various steels for a three-point bending. Effect of the distance between the specimen supports (span length) on fatigue resistance was investigated. As in the roll situation, this factor is characterized by the coefficient of arm $_{lb}$ as the ratio of the specimen height to the half-length of the span. With its decrease and increase in the stress gradient including that occurring in the longitudinal direction of the specimen, regularities of crack growth change. The semicircular crack with the ratio of semi-axes $c/a=1$ (Fig. 3) originated on the elongated bottom face of the specimen tends to turn into a rectilinear edge crack of breakaway when spans increase. If the maximum cyclic stresses are sufficiently high to reach critical SIF $K_{Ifc}$, then fracture occurs when the crack front is still curvilinear. The surface crack grows more intensively in the bottom face.

When the span decreases, the rate of growth in this direction decreases and the $c/a$ ratio increases, that is, the crack retains a round shape for a longer time. A further span decrease results in that the current shape of the fracture changes noticeably: the value of $c/a$ ratio becomes larger than one since a more intensive crack growth upward along the lateral face is observed. To quantify the crack shape, relationship between the $c/a$ ratio and its relative depth c/D is used. Usually, a power function is used for this model but one can limit himself to a linear dependence in this case: $c/a=1+q(c/D)$. Intensity of the change of the shape of $q$ is: $q=-1.2(\gamma_{lb}=5)$; $q=-0.7(\gamma_{lb}=2)$; $q=0.1(\gamma_{lb}=1)$ (Fig. 3).

It is quite obvious that with the growth of the arm coefficient, influence of the II mode of fracture increases.

The critical value of the crack depth $c_c$ obtained for the conditions of $\gamma_{lb}$=5 is not the same for the conditions of $\gamma_{lb}$=1 and does not lead to an instant brittle fracture. Instead, crack growth with a rate of $10^{-7}$ to $10^{-6}$ m/cycle is observed in the direction of maximum shear stresses $\tau_{sh}$ where there are no bending stresses. In this case, the cracks start to deviate from the direction perpendicular to the bottom face which is typical for the transverse shear. In analysis of the mixed fracture, the limiting state was estimated by the equivalent SIF:

$$K_e = \left(K_I^2 + K_{II}^2\right)^{0.5},$$

where $K_{\mathrm{I}}$ and $K_{\mathrm{II}}$ are the effective SIF for the corresponding mode [19]. For edge cracks, taking into account the calibration corrections applied to $K_{\mathrm{I}}$ and $K_{\mathrm{II}}$ [20], shear strains increase $K_e$ by 12–15 % and reduce the value of $c_c$ by one-third or one-quarter.

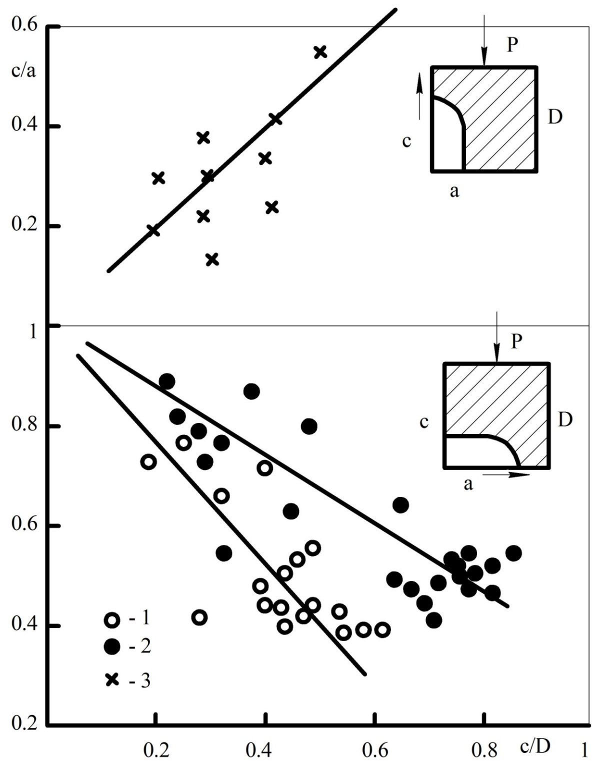



Fig. 3. Change in the crack shape in prismatic specimens of low-alloy steels in a three-point bend: $\gamma_{Lb}$=5 (1); $\gamma_{Lb}$=2 (2); $\gamma_{Lb}$=1 (3)

Another feature of behavior of materials in transverse bending is associated with an increase in the cyclic strength with reduction of the span if normal stresses are used for the criterion. Fatigue tests of a viscous 09Mn2 steel ($\sigma_B$==462 MPa, $\sigma_T$=328 MPa, $\psi$=0.56) testify to this: when the arm coefficient is reduced from $\gamma_{lb}$=2.5 to $\gamma_{lb}$=1, the fatigue limits expressed in the maximum conditionally elastic stresses of the cycle increase by 20 %. It can be assumed that this difference for the true stresses will be insignificant taking into account the early appearance of plastic deformations in the given steel. However, for thermally strengthening steels, e. g., 40X steel, ($\sigma_B$=1480 MPa, $\sigma_{0.2}$=1180 MPa, $\psi$=0.43), an increase in durability is observed, practically by an order of magnitude $\gamma_{lb}$=2.5 to $\gamma_{lb}$=1. In this situation, the true bending stresses are approximated to conditionally elastic normal stresses. Here, the arm factor $\gamma_{lb}$ manifests itself in the same way as the stress concentration factor but unlike it, the fatigue limit in the multi-cycle region does not decrease. This is because of the nature of distribution of normal stresses at $\gamma_{lb}$=1 and deformation of the cross sections in transverse bending (Fig. 2, *b, c*). The above facts convince that normal stresses for the working conditions of rolls do not completely control the processes of accumulation of fatigue damages in the roll body.

**4. 2. The history of the roll loading**

The roll metal is under conditions of a complex stress state for which criterion of equivalent ultimate state is usually established. For large sections, such models are not always reliable. Currently, the local-deformation approach is more effective, assuming that the elementary volume of the metal (defect) is successively subjected to various types of deformations resulting in a mixed (combined) load history. In this aspect, histories of stress variation during on roll revolution for all fracture modes have been developed (Fig. 4).

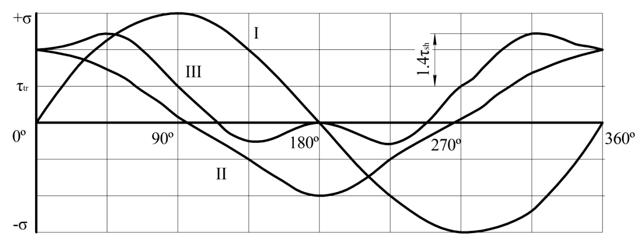



Fig. 4. Variation of stresses at a mixed roll loading for the I, II, III failure modes

Main parameters of cyclic process, i. e. the range of stresses $\Delta\tau$ and $\Delta\sigma$ as well as the coefficient of cycle asymmetry $R$ are calculated by formulas:

$$\Delta\sigma_{\mathrm{I}} = \sigma, \quad R_I = -1; \tag{5}$$

$$\Delta\tau_{\mathrm{II}} = 2.8\cdot\tau_{sh}, \quad R_{\mathrm{II}} = -1; \tag{6}$$

$$\Delta\tau_{\mathrm{III}} = 2\left(1.4\tau_{sh} + \tau_{tr}\right), \quad \Delta\tau_{\mathrm{III}} = 2\left(1.4\tau_{sh} + \tau_{tr}\right). \tag{7}$$

Presence of the III mode is determined not only by the torque transfer by the rolls but also by the change of direction of the tangential stresses $\tau_{sh}$ relative to the defect. These stresses are amplitude-related for the process III and the stresses from torsion $\tau_{tr}$ play here the role of the mean cycle stress.

For the work rolls of quarto stands, the bending and shearing stresses are determined by the forces of the counter-bending system and for the back-up rolls, torsional stresses are determined by the idle stroke moment.

**4. 3. Determination of the defect development rate by the method of survivability curves**

By integrating the Paris equation, a relationship between the crack growth period $N$ and the effective nominal stresses $\sigma$ are obtained. The range between initial and final crack dimensions is taken here as a parameter. By analogy with the fatigue curve, such $\sigma$-$N$ diagram can be called the survivability curve. Having obtained the survivability curves for each mode of breakage, it is possible to calculate total life for a mixed non-stationary process by summing up relative lives [2, 6].

In the analytical form, this integration can be carried out if the calibration correction to the SIF does not depend on the crack depth. In this case, it is a circular (in the cross-section) crack which was taken for the model of a permissible defect [11, 12] as applied to the rolls. Such somewhat simplified model looks legitimate since the globular nonmetal microscopic inclusions found in metals cause fracture in the contact-fatigue processes [21, 22]. This makes it possible to use formulas of the same type to calculate the acting SIF [11, 12]:

$$\Delta K_{\mathrm{I}} = 1.13 \cdot \Delta\sigma_{\mathrm{I}}\sqrt{a};\;\; \Delta K_{\mathrm{II}} = 1.33 \cdot \Delta\tau_{\mathrm{II}}\sqrt{a};$$

$$\Delta K_{\mathrm{III}} = 0.93 \cdot \Delta\tau_{\mathrm{III}}\sqrt{a}. \tag{8}$$

A schematic diagram of fatigue failure for various modes has been developed applied to the roll materials. Having adopted the SIF threshold value for the second mode $\Delta K_{\mathrm{IIth}}$=4 MPa·m$^{0.5}$, conditionally critical SIF $\Delta K_{\mathrm{I}}$*=$\Delta K_{\mathrm{II}}$*=40 MPa·m$^{0.5}$, $\Delta K_{\mathrm{III}}$*=53 MPa·m$^{0.5}$ (corresponding to the crack growth rate $v=10^{-7}$ m/cycle) were determined using the obtained model. Threshold SIF are set as: $\Delta K_{\mathrm{Ith}}$=12.6 MPa·m$^{0.5}$ (corresponds to $v=10^{-9}$ m/cycle), $\Delta K_{\mathrm{IIIth}}$=5.3 MPa·m$^{0.5}$ (corresponds to $v=10^{-10}$ m/cycle, as for $\Delta K_{\mathrm{IIth}}$). This gives the following indices of inclination of the Pary's section in the diagram: $n_{\mathrm{I}}=4$, $n_{\mathrm{II}}=n_{\mathrm{III}}=3$. For the value of $n=3$, solution of the Paris equation for determining the number of cycles of survivability is known:

$$N_i = \frac{2\cdot 10^7\left[\Delta K_i^*\left(1-R_i\right)^{\chi_i}\right]^3}{\pi^{1.5}\left(\Delta\tau_i\cdot f_i\right)^3\cdot\sqrt{a_{0i}}}\cdot\left(1-\sqrt{\frac{a_{0i}}{a_{ci}}}\right), \tag{9}$$

where $i$=I, II, III is the failure mode; $\chi_i$ is the SIF sensitivity to the cycle asymmetry; $f_i$ is the calibration correction ($f_{\mathrm{II}}=0.75$, $f_{\mathrm{III}}=0.52$); $a_0$ and $a_c$ are the initial and final radii of the defect, respectively.

Here, the value $a_0$ implies the initial size of the defect from which the final stage of its development starts and finishes with a "volumetric" failure of the roll. It was defined as:

$$a_{0i} = \frac{\left[\Delta K_{ith}\cdot\left(1-R_i\right)^{\chi_i}\right]^2}{f_{ia}\cdot\Delta\tau_i^2}, \tag{10}$$

where $f_{\mathrm{I}a}=1.28$, $f_{\mathrm{II}a}=1.77$, $f_{\mathrm{III}a}=0.85$ are correction coefficients for determining the defect size.

It was assumed that $\chi_{\mathrm{I}}=0.75$, $\chi_{\mathrm{II}}=\chi_{\mathrm{III}}=0.5$ and for $a_I$, it is necessary to substitute $\Delta\sigma$ in (6).

The final value of $a_c$ can be chosen as a critical proceeding from the brittle fracture conditions or from the possibilities of the roll diagnosing. In this case, it is convenient to take a 100-fold increase in the initial defect which actually can be detected during operation. For the value $\gamma_{1b}=0.25$ taken in the example, the critical value $a_{0\mathrm{I}}>100a_{0\mathrm{II}}$ which excludes contribution of the I mode at this stage of fracture. Influence of the factor $a_c$ on the survivability period is less significant than the influence of other factors which is explained by the high crack growth rates as it approaches the critical size [23].

Combining equations (5) and (6), equations of the inclined sections of the survivability curves are obtained:

$$\Delta\tau_i^2\cdot N_i = B_i, \tag{11}$$

where $B_{\mathrm{I}}=B_{\mathrm{II}}=9.7\cdot 10^9$ for the 1st period of fracture due to the II mode when $a_{\mathrm{cII}}=a_{0\mathrm{III}}$; $B_{\mathrm{I}}=B_{\mathrm{II}}$'$=8.5\cdot 10^9$ for the 2nd period of fracture due to the II mode when $a_{\mathrm{cII}}=100a_{0\mathrm{II}}$; $B_{\mathrm{I}}=B_{\mathrm{III}}=73.6\cdot 109$ for the 2nd period of fracture due to the III mode when $a_{\mathrm{cIII}}=a_{\mathrm{cII}}=100a_{0\mathrm{II}}$.

Equality of the exponent in equation (7) $m=2$ follows unambiguously from (5) and (6) for the accepted models of fracture resistance. This causes a rather steep inclination of the survivability curves which speaks of a relatively weak influence of stresses on the period of crack growth.

Then, for the set of stresses with parameters of the steps $\Delta\tau_{shj}$ and $C_j$ (relative duration), an equivalent stress is determined by formula

$$\tau_{she} = \sqrt{\Sigma C_j\cdot\Delta\tau_{shj}^2}$$

and then it is possible to find equivalent crack growth rates (Table 1) as the ratio of the interval ($a_c-a_0$) to the period $N$. From the survivability curves (7), the number of cycles $N_{\mathrm{II}}$ is determined for the first period of fracture which corresponds to the number of revolutions of the roll. The number of cycles $N_{\mathrm{II}}$' and $N_{\mathrm{III}}$ for the second period of fracture is also determined.

Table 1

Determination of the rates of development of a circular defect for the roll body zone where $\gamma_{1b}=0.25$ for $\gamma_{1h}=0.0025$ and $a_{\mathrm{cII}}/a_{0\mathrm{II}}=100$

| $\tau_{she}$, MPa | $a_{o\mathrm{II}}$, mm | $a_{o\mathrm{III}}$, mm | $N_{\mathrm{II}}\cdot 10^{-7}$, rev. | $N_{\Sigma 2}\cdot 10^{-7}$, rev. | $v_{\mathrm{II}}\cdot 10^{10}$, m/rev. | $v_{\Sigma 2}\cdot 10^{8}$, m/rev. |
|---|---|---|---|---|---|---|
| 5 | 40 | 148 | 38.5 | 30.4 | 2.8 | 1.0 |
| 10 | 10 | 37.0 | 9.6 | 7.6 | 2.8 | 1.27 |
| 15 | 4.5 | 16.,7 | 4.1 | 1.9 | 2.98 | 2.2 |
| 20 | 2.5 | 9.2 | 2.4 | 1.9 | 2.8 | 1.27 |
| 25 | 1.6 | 6.0 | 1.5 | 1.2 | 2.85 | 1.28 |
| 30 | 1.1 | 4.1 | 1.1 | 0.9 | 2.8 | 1.25 |
| 35 | 0.8 | 3.0 | 0.8 | 0.6 | 2.8 | 1.2 |

When the roller is subjected to a combined loading by the II and III modes (the second period), the number of cycles of survivability will be:

$$N_{\mathrm{II+III}}=[0.5\,((1/N_{\mathrm{III}})+(1/N_{\mathrm{I}}'))]^{-1}. \tag{12}$$

In the roll speed numbers, this will be half: $N_{\Sigma 2}=0.5\,N_{\mathrm{II+III}}$. The total number of revolutions of the roll which determines its survivability will be:

$$N_{\Sigma}=N_{\mathrm{II}}+N_{\Sigma 2}. \tag{13}$$

Different growth rates $v_{\mathrm{II}}$ and $v_{\Sigma 2}$ are observed in the periods 1 and 2 but as follows from the results their value, is practically independent of the level of tangential stresses. In the period 1, $v_{\mathrm{II}}=2.8\cdot 10^{-10}$ m/rev. can be taken, and in the period 2, $v_{\Sigma 2}=1.25\cdot 10^{-8}$ m rev. Calculations for $\tau_{she}$=5 and 10 MPa should be considered as conditional since the chosen value of $a_c$ is larger than the roll dimensions. Here, calculations of velocity $v$ are of interest.

## 5. Discussion of the results obtained in the study of the roll survivability

To diagnose the rolls, the results obtained in the study make it possible to use the crack growth curve approximated by two straight sections with different slopes proportional to the rates $v$ (Fig. 5). Constancy of the crack growth rate for the mixed fracture mechanism is confirmed by the fatigue tests of specimens with shorter spans presented above: fracture occurred smoothly up to the specimen disintegration without a characteristic jerk that makes the test machine shake. The larger value of $\tau_{she}$ corresponds to the smaller value of $a_{0II}$ and $a_{0III}$ which reduces both survivability $N_{II}$ and its total period $N_{\Sigma}$.

This conclusion is of high practical importance. Operating conditions of the rolls in different stands of the rolling mill differed considerably from each other. Work rolls of the reducing and pre-finishing stands are subject to considerable dynamic and thermal loads. This is explained by the large reductions with a long arc of contact of rolls with the rolled metal and a low speed of their rotation (several tens of rpm). In the last finishing stands, a significant decrease in strip temperature was observed resulting in a decrease in the strip metal plasticity. This brought about a significant shortening of the contact arc. At the same time, the mechanical loads acting on the rolls remained at a considerably high level and the loads decreased in magnitude and frequency. The speed of rotation of the rolls in the last finishing stands was several hundred rpm. Thus, viscosity of the core of these rollers must be matched to the high hardness of their working layer. Rolls of intermediate stands perceive high loads, both mechanical and thermal, and obviously are in the most vulnerable state. A question arises in which stands the rolls are damaged more intensively.

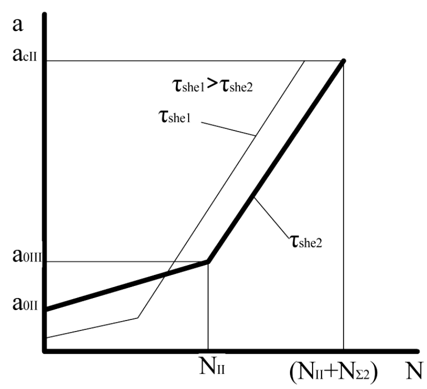



Fig. 5. Schematic graphs of development of a circular defect for various values of $\tau_{she1}$ (thin line) and $\tau_{she2}$ (heavy line) in the roll

The speed of rotation of rolls of the '1680' plate-rolling mill was in the range from 20 to 500 min$^{-1}$. According to the obtained data (Table 1), for the value $\tau_{she}$=20 MPa (which is established for many mills and is considered safe), the service life was from 1433 to 35,833 hours. Achievement of this range is observed in production conditions. This confirms relevance of the problem of necessity to diagnose the roll stock and the rational route of their rearrangement in cages. In the considered case, the running time of the roll (the total number of revolutions) was a sufficient diagnostic parameter for evaluating its technical state. This is usually performed by ultrasonic testing. After detecting a defect of size $a_0$, the date of the next check must be set. If the size of the defect is $a_0 > a_{0II}$, then the number of revolutions of the roll until the limit size $a_c$ is:

$$N_{\Sigma} = \frac{a_0 - a_{0III}}{v_{II}} + \frac{a_c - a_{0III}}{v_{\Sigma 2}}. \qquad (14)$$

The optimal inter-control interval will be equal to half the life $N_{\Sigma}$ found by (10) [24]. However, in order to use this algorithm, it is necessary to estimate in detail characteristics of fracture resistance of the roll material.

During their operation, rolls are subjected to a number of damaging factors that lead to their inoperable state when quality of the rolled product deteriorates and to the loss of operability when rolling is impossible. The defective state, as a rule, precedes the inoperable state. The first state is associated with the surface damaging processes and the second with "volumetric" destruction. Although the roll surface is periodically restored, crack-like defects, which were developed from the surface phenomena remain in the near-surface layers of the barrel and in the roll necks. The mechanism that leads to the gradual development of such a defect has been identified.

In the tests of viscous and brittle steels under conditions of transverse bending, features of change of the crack front shape with the crack growth were observed and the influence of the coefficient of the bend arm $\gamma_{1b}$ on the cyclic strength was also established. These facts, together with analysis of roll fracture, indicate that the tangential shear stresses induced by the rolling force can play a key role in such fracture. This is explained by the low threshold values of the SIF II mode for roll materials and the fact that the stresses $\tau_{sh}$ form a symmetric cyclic process of the II mode in each roll revolution. In addition, the change in direction of the tangential stresses relative to the defect generates an asymmetric cyclic process of the III mode during rotation of the roll transmitting torque. The sequence of changes of stresses in one revolution of the roll was established to form parameters of the mixed fracture mechanisms.

The proposed solutions are of a particular relevance for relatively short rolls of tube rolling mills. For such rolls, the number of failures connected with the defective work surface is smaller in comparison with the failures caused by fracture of shanks and necks. This is because of growth of the effect of the transverse stresses induced by the rolling force.

An algorithm for predicting the survivability period was developed based on a linear defect growth model. The problems of effect of the mixed mechanism of failure and non-stationary loading of rolls were solved by the method of survivability curves. This approach was demonstrated earlier in [25]. It was further developed in this work which allowed us to establish new regularities. It is of interest to use the method of survivability curves for the scenarios of the mixed fracture of the contact surface of rolls.

Similar models of solids under conditions of cyclic interaction are based on the criteria of material fracture during growth of fatigue cracks. The residual service life was estimated using the algorithm of incremental crack growth developed by the method of singular integral equations of the theory of elasticity for bodies with curvilinear cracks. As a result, models of residual contact durability were established which, in fact, are the survivability curves for the steels used in making rolls, rails and wheels [26].

For the II and III modes of failure, survivability curves of the inner transverse circular crack have an inclination index $m$=2. The gradual growth of defect by the II mode provokes appearance of an additional process of failure by the III mode which is accompanied by a noticeable jump of the crack growth rate (more than 200 times). Within the framework of the developed model, the stress level affects the period of survivability by variation of initial and critical dimensions of the defect for the corresponding failure mechanism.

## 6. Conclusions

1. As a result of study of the effect of internal strength factors on spherical defects in the roll body, a scenario of the roll fracture under the action of the mixed mechanism was revealed. An important role in this process is played by deformations of the II mode which were taken into account earlier only when evaluating degradation of the roll surface. The contribution of tangential shear stresses from the rolling force to the process of volumetric fracture of rolls has not been taken into account up to this time.

2. The mixed mechanism of fracture leads to an increase in the defect growth rate by more than two orders of magnitude. Residual life and survivability of the roll are reduced in the same proportion. A reliable prediction of these indicators makes it possible to effectively operate rolls and maximize the degree of use of the service life.

3. An algorithm for predicting residual service life of rolls was developed on the basis of the method of survivability curves. Testing of this algorithm in the conditions of the continuous hot plate-rolling mill proved the possibility of using an algorithm of monitoring the residual service life of the rolls. At the same time, the diagnostic parameter is the working time of the roll.

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# A METHOD DEVELOPED TO CALCULATE LATERAL EARTH PRESSURE ON A SHEET PILE WALL WITH COUNTERFORTS


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***Розроблено метод розрахунку бокового тиску грунту на шпунтову стінку з контрфорсами різної форми – прямокутної, трапецеїдальної з розширенням донизу, трапецеїдальної з розширенням догори. Проведено математичне моделювання системи «шпунтова стінка з контрфорсами – грунтове середовище». Досліджено епюри бічного тиску грунту на шпунтові стінки з контрфорсами. Отримано кількісна оцінка розвантажуючої дії контрфорсів різної форми***



***Ключові слова: метод розрахунку, шпунтова стінка, контрфорси, боковий тиск грунту, розвантажувальний вплив***



***Разработан метод расчета бокового давления грунта на шпунтовую стенку с контрфорсами различной формы – прямоугольной, трапецеидальной с расширением книзу, трапецеидальной с расширением кверху. Проведено математическое моделирование системы «шпунтовая стенка с контрфорсами – грунтовая среда». Исследованы эпюры бокового давления грунта на шпунтовую стенку с контрфорсами. Получена количественная оценка разгружающего действия контрфорсов различной формы***



***Ключевые слова: метод расчета, шпунтовая стенка, контрфорсы, боковое давление грунта, разгружающее влияние***


## 1. Introduction

The development of the ports of Ukraine requires the construction of deepwater berthing facilities for servicing modern large-tonnage vessels. The existing construction solutions for deepwater berths are labor-intensive and material-intensive if they require, for example, complex tonguing and grooving [1, 2] or using transverse rows of sheet piles [3]. Therefore, it is necessary to develop and implement innovative design solutions in hydraulic engineering. Nowadays, the most rapidly constructed structures are sheet pile walls [4], so the creation of new design solutions with sheet piles is important. One of the proposed solutions is a sheet pile wall with counterforts [5], which has received a patent for the invention itself [6] and a utility patent for the construction method [7]. Counterforts contribute to a significant reduction of lateral earth pressure on the front wall and a rational distribution of material in the construction. However, the use of a new design in practice necessitates the development of a method for calculating the lateral earth pressure, taking into account the relief effect of the counterforts. It is also necessary to conduct research on the stress-strain state of the system "a sheet pile wall with counterforts plus the soil environment". The solution of the task is an important link in the study of the new type of construction, which will allow introducing it into engineering practice.

## 2. Literature review and and problem statement

The main load on retaining walls is produced by lateral earth pressure. To study the joint effect of the soil backfill and the construction, numerical calculation models [8] are developed and approaches for optimal design are sought [9]. In order to reduce earth pressure on the retaining wall, various relief devices are offered, such as horizontal shelves located on the backfill side [10, 11] or a relief platform [12].

Counterforts are also one of the types of relief elements in the structure. Calculation methods for defining the relief influence of counterforts are based on theoretical, laboratory and field studies. Moreover, a method has been proposed for calculating the screening effect of counterforts, which provides for correcting the active earth pressure using empirical dependence obtained on the basis of tests [13]:

$$\sigma = (\gamma z + q)\lambda_a (1-k), \tag{1}$$