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Analytical testing and methods for increasing the durability of plunger hydraulic cylinders

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Abstract. The article deals with the important problem of increasing the operating life of roll-balance system plunger hydraulic cylinders and describes the solution to this problem. The durability of plunger hydraulic cylinders determines not only the overall reliability of a hydraulic system, but also the technical and economic efficiency of the whole wide-strip hot rolling mill. Hydraulic cylinder durability depends primarily on the wear resistance of sealing units. Therefore in order to provide an effective approach to increasing the hydraulic cylinder life we have developed an analytical method for determining wear resistance of sealing units (i.e. determining a class or category) and calculating their expected operating life. The method is based on the solution of the fundamental equation of energy and mechanical theory of stationary units wear-fatigue as well as the theoretical provisions describing the strain pattern, initial and limiting values pertaining to plunger cylinders sealing units operating conditions. We have performed a computer experiment to study the behavior of various sealing materials and plungers with different antifriction coatings. As the result of the experiment we have established a number of ways to improve wear resistance of sealing units and durability of hydraulic cylinders by utilizing more durable elastomers and application of double-layer metal-polymer coatings. The most reliable design options of sealing units have been pilot tested and put into operation.

1 Introduction

Practice has shown that the durability of hydraulic roll-balance systems used in wide-strip hot rolling mills is primarily dependent on the useful life of plunger hydraulic cylinders sealing units. A highly relevant issue of the sealing units reliability theory is forecasting the sealing units wear resistance and durability by applying modern physico-mathematical models. As early as the design stage, such models make it possible to not just carry out the analytical assessment of the tested couplings (i.e. to ascertain their wear resistance class/category $(КИ/_P)$ according to the algorithm by I. V. Kragelsky [1, 2]), but also to forecast the expected life of a unit with a sufficient degree of confidence. These objectives acquire pressing importance when working on the design of hydraulic devices sealing units.

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All the more so because slave plunger hydraulic cylinders (fig. 1) are used in hydraulic roll-balance systems (ensuring high precision of roll movement and positioning within the stand) of almost every modern wide-strip hot rolling mill.

In rolling operation there is a discrepancy of clearances l_{nep} between the roll chocks of the upper (7) and lower (8) working rolls in relation to the housing post (9) of the stand. Such discrepancy creates a resultant friction force $F_t = f_n \cdot G$, with which the roll chock surface (7) affects the plunger end (1). Here f_n is the coefficient of friction between the upper roll chock (7) and the plunger end (1); G is the share of upper rolls and chocks weight per one plunger. Tilting moment of the plunger (1), created by the force F_t , is counterbalanced by reacting torque $N_{вт}$ of bronze guide bushing (3) and press bushing (4). Vertical fluctuations of plunger 1 are generated by impact stress of each strip end passing through the deformation zone. They lead to wear of all elements, such as sealing (2), bushing (3, 4) and plunger (1).

As shown by practice, the wear rate of sealing units (2) is much higher than that of bronze bushings (3, 4) and steel plunger (1). Therefore, the primary cause of hydraulic cylinders failure and shut-down of a mill for maintenance and repairs is the loss of tightness of sealing joints (2). This is caused by wear process and cylinder pressure drop due to leakage of working fluid. In other words, wear resistance class of 'plunger (1) – sealing (2)' joints determines not only the useful life of hydraulic cylinders, but also the overall reliability level of the hydraulic system and technical and economic parameters (efficiency) of the rolling mill. Therefore it is very important to solve the problem of substantial improvement of the sealing units wear resistance and durability.

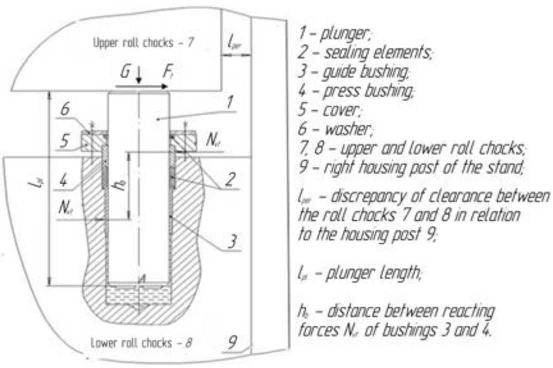

Fig. 1. Plunger hydrocylinder.

When dealing with this kind of challenges, it is common practice to run long-term tests of laboratory or full-scale specimens at the stage of hydraulic equipment design. The more so with newly developed, unique objects. Such approach has substantial time and cost implications. We believe it is possible to reduce or eliminate such expenses by adopting an analytical approach to this issue. This approach allows us to avoid laboratory and full-scale testing. It is based on mathematical modeling of hydraulic cylinders failure process by the criterion of sealing elements wear resistance.

Therefore, the aim of this work is to:

– develop an analytical method of diagnosing wear resistance and calculating expected life of the hydraulic cylinders sealing units;

– provide theoretical research on wear resistance of modern sealing materials under various friction conditions and select effective solutions for increasing the plunger hydraulic cylinders durability.

This objective can be achieved by using a kinetic approach to description of damageability and destruction of mechanical structures [3-6], fundamental principles of technical objects parametric reliability theory [7-10] and the main provisions of energy-mechanical concept of friction units durability [11, 12] obtained by simultaneous solution of molecular-mechanical [13] and structure-energy theories of friction [5, 14, 15].

2 Analytical method for testing wear resistance of sealing and calculation of plunger hydraulic cylinders useful life

For the purpose of developing this technique let us assume that the ‘plunger (1)-sealing (2)’ friction pair will operate in a stationary mode at a steady average rate of fatigue wear $\dot{y} = const$ of sealing elements, while retaining sufficient tightness to prevent penetration of abrasive particles into the joint.

Project evaluation technique for determining a wear resistance class/category of a sealing unit and forecasting the useful life of hydraulic cylinders can be presented as a sequence of the following calculations, made in consistence with the provisions of paper [1].

Operation 1. Let us determine a dimensionless parameter of sealing unit wear resistance by the following equation [1]:

$$И = \Delta L / \Delta H = V_{sk} / \dot{y}, \tag{1}$$

where $\Delta H = \dot{y} \cdot t$ is the radial wear of a sealing in time t at the wear rate $\dot{y}$ (at the distance of friction $\Delta L = V_{sk} \cdot t$); V_{sk} - sliding speed.

According to paper [1], the parameters of the equation (1) should be set by statistical processing of the data provided under laboratory or full-scale tests of friction pair samples. In order to make analytical assessment of the wear resistance index let us use the following fundamental equation of energy and mechanical wear concept [11, 12], derived for ‘stationary’ sealing joints [16, 17]:

$$\dot{y} = \alpha^* \cdot \nu \cdot f^y_{mech} \cdot p_{\max} \cdot V_{sk} / \Delta u_{e*}, \tag{1.1}$$

Where $\alpha^* = 1$ is the coefficient of mutual overlap of the sealing friction area;

$p_{\max}$ - is the maximum contact stress of plunger (1)-sealing (2)’ friction pair;

ν_2 - is the energy conversion ratio, representing the transformation of external energy into the internal energy of sealing material;

$f^y_{мех}$ - is an average value of friction coefficient mechanical component in steady-state conditions;

Δu_{e*} - is the maximum energy intensity of sealing material.

Values of ν_2, $f^y_{мех}$, Δu_{e*} are defined according to paper [16].

Maximum contact stress values of ‘plunger (1)-sealing (2)’ friction pair are calculated for their strain (loading) pattern, fig. 2ab, by the following equation:

$$p_{\max} = p^{y}_{a\max} + p_{sg}\,, \tag{1.2}$$

where $p^{y}_{a\max}$ is the maximum stress acting at the most heavily loaded point E of contact between plunger and sealing, calculated according to the well-known method of evaluating tightened joints [13] subjected to external pressures (loading) F_t and $q(y)$ fig. 2;

p_{sg} is the stress, emerging due to contraction of a sealing by a specified amount, determined by the condition of their volume constancy;

Operation 2. Let us write the wear resistance index in exponential form [1]:

$$И = \alpha \cdot 10^{КИ}\,. \tag{2}$$

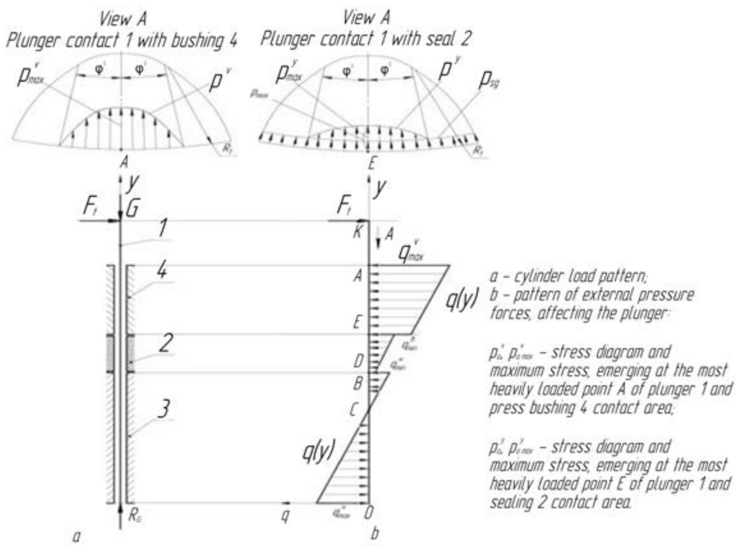

Fig. 2. Load pattern for plunger hydraulic cylinder elements.

Operation 3. Let us determine the wear resistance class of the test sample or friction joint by assigning to it an integer value $КИ$ - the exponent of 10 in Operation 2, setting the number range from 3 to 12 [1]:

$$КИ = 3,\ 4,\ 5,...12\,. \tag{3}$$

Operation 4. Let us determine the sample wear resistance category from 1 to 5: $p = 1,\ 2,\ ...5,$ depending on the interval of values, which the number α, obtained by calculations of *Operation 2* falls into.

$$\begin{aligned} p &= 1\text{, if } 1{,}0 \le \alpha < 1{,}59\,; \\ p &= 2\text{, if } 1{,}59 \le \alpha < 2{,}51\,; \\ p &= 3\text{, if } 2{,}51 \le \alpha < 3{,}98\,; \\ p &= 4\text{, if } 3{,}98 \le \alpha < 6{,}31\,; \\ p &= 5\text{, if } 6{,}31 \le \alpha < 10{,}0\,. \end{aligned} \tag{4}$$

For example, if the wear resistance index of the joint under test is defined by the number $И = 7{,}71 \cdot 10^8$, then the wear resistance class and category of this tribounit will be equal to $КИ/_P = 8/_5$ [1].

Operation 5. Let us calculate the useful life of a sealing unit from the specified permissible wear amount $[y]$ and the theoretical wear rate $\dot{y}$ derived from calculations in step (1.1):

$$\bar{t}_* = [y]/\dot{y}\,. \quad (5)$$

Analytical technique (1) – (5) is then used for theoretical assessment and improvement of wear resistance and life of plunger hydraulic cylinders operating in the roll-balance system of wide-strip rolling mills.

3 Computer experiment plan and the results of theoretical studies

The experiment consisted of three groups of virtual tests (see the table), in each of which five different sealing antifriction materials were subjected to "friction fatigue" in various rubbing conditions:

- against the surface of the plunger after its grinding without coatings;
- against the surface of the plunger with a "brass (L63)- fluorocarbon polymer (F4*)" double-layer antifriction coating;
- against the surface of the plunger with an "aluminium alloy (D16)- fluorocarbon polymer (F4)" double-layer anticorrosive and antifriction coating.

Seal materials used in the experiment consisted of fluorocarbon polymer (F4, Ecoflon 1) and elastomers (rubber SKN, polyurethane Ecoruber 2 and Ecopur) [18-20]. Plunger was made of 40X steel grade*. Plunger coatings with a required set of physical and mechanical properties are formed by way of cladding with the help of coated abrasive tools [16]. External loading conditions were identical for all test groups and correspond to the real operating conditions of hydrocylinders installed in the fifth stand of the finishing mill group at 2500 Hot Rolling Mill (Magnitogorsk, Russian Federation). These conditions are as follows: $F_t = 29{,}25\ кН$; $V_{ск} = 1{,}94 \cdot 10^{-2}\ м/с$, $[y] = 1{,}25 \cdot 10^{-3}\ м$.

The results of theoretical studies for all sealing units modifications, i.e. the assessment of values $(КИ/_P)_i$, useful life t_{npi} and durability increment $K_{P\,i} = t_{npi}/t_{np1}$, calculated according to techniques (1)-(5) are given in columns 4-6 of table 1, where i stands for the number of test.

It is obvious that under the given operating conditions all the considered options of sealing units belong to wear resistance class 5 - $КИ = 5$. However, due to the use of modern seal materials (as compared with the type of rubber (SKN-26) used at the rolling mill) and application of antifriction coatings on plunger surface, over sixty percent of "plunger-sealing" friction pairs migrate from the first category of wear resistance ($КИ/_P = 5/_1$) to the fourth or fifth category $КИ/_P = 5/_{4-5}$. The corresponding tests are highlighted by dark background in Table 1.

Due to improvement of the seal wear resistance in the first group it is reasonable to expect an increase of a hydraulic cylinder lifespan by a factor of $K_{P2-5} = 2{,}0 \div 3{,}8$. Application of brass-fluorocarbon or duraluminum-fluorocarbon coatings on a plunger surface allows us to forecast an extra increment of operating life by a factor of $K_{P\,7-10} = 2{,}9 \div 5{,}8$ or $K_{P\,12-15} = 2{,}6 \div 5{,}2$, respectively. See Table 1.

Table 1. The Results of Theoretical Studies on the Wear Resistance and Durability of Various Hydraulic Cylinder Modifications.

Test №	Plunger material – steel of grade 40X / Sealing material	Wear rate, $\dot{y} \cdot 10^{-7}$, $m/\sec$	Wear resistance class & category $(КИ/_P)_i$	Average operating life, t_{pri}, *hour*	Operating life increment ratio $K_{P\,i}$
Group 1 – without coating					
1	SKN-26	1.40	$5/_1$	2.48	1
2	F4	0.69	$5/_3$	5.00	2.0
3	Ecoflon 1	0.48	$5/_3$	7.17	2.9
4	Ecoruber 2	0.44	$5/_4$	7.94	3.2
5	Ecopur	0.38	$5/_4$	9.20	3.8
Group 2 - L63+F4 coating					
6	SKN-26	0.985	$5/_2$	3.53	1.4
7	F4	0.488	$5/_4$	7.11	2.9
8	Ecoflon 1	0.339	$5/_4$	10.17	4.1
9	Ecoruber 2	0.293	$5/_5$	11.87	4.8
10	Ecopur	0.241	$5/_5$	14.38	5.8
Group 3 - D16+F4 coating					
11	SKN-26	1.04	$5/_2$	3.33	1.3
12	F4	0.537	$5/_3$	6.46	2.6
13	Ecoflon 1	0.377	$5/_4$	9.18	3.7
14	Ecoruber 2	0.331	$5/_4$	10.50	4.2
15	Ecopur	0.270	$5/_5$	12.85	5.2

4 Practical implementation of the theoretical results

The results of theoretical studies on the subject of increasing the hydraulic cylinders durability by using advanced sealing materials and antifriction coatings on plunger surface, have made it possible to recommend for industrial use the following modifications of "plunger-sealing" friction units:

- "plunger with L63+F4 double-layer coating and Ecopur polyurethane sealing". The modified unit expected operating life is more than three-fold higher than that of the original design.
- "plunger with D16+F4 double-layer coating and Ecopur polyurethane sealing". The modified unit expected operating life is more than two-fold higher than that of the original design.

The most reliable design options of plunger hydraulic cylinders with wear resistance class of "plunger-sealing" friction units equal to $КИ/_P = 5/_{4-5}$ have been pilot tested, protected by patent to an improved model [21] and put into operation [4, 12].

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