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Enhancement of the Service Life of Hydraulic Cylinders through Optimization of Sealing Element Parameters

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Abstract

In this work a comprehensive investigation aimed at increasing the service life of hydraulic cylinders by tuning the parameters of their sealing components is carried out. The significance of the study is determined by the economic losses incurred during downtime and major overhauls of heavy construction and mining machinery, in which hydraulic cylinders often constitute the primary vulnerable elements. The objective of the research is to propose and substantiate a methodology for selecting and optimizing seals capable of improving wear resistance and, consequently, extending the overall lifespan of the hydraulic cylinder. The methodological foundation of the work includes a review of recent publications in the fields of materials science and seal tribology, a detailed study of the physicochemical and mechanical wear mechanisms, as well as a synthesis of data on the refurbishment of hydraulic cylinders under operational loads. As baseline information, the results of repair and modernization of machines of the Caterpillar and Komatsu brands are utilized. The findings of the study consist in the systematization of factors determining the wear intensity of sealing elements and the creation of an algorithm for their selection with regard to various operating modes. A comparative analysis of the operational characteristics of seals made of polyurethane (PU), polytetrafluoroethylene (PTFE) and their composite modifications is presented. The scientific novelty of the work lies in the proposal of an integrated approach combining the selection of the optimal sealing material, its geometric configuration and mating surface parameters with advanced restoration technologies, which ensures maximal extension of the hydraulic cylinder life cycle. The practical significance of the results is that they can be employed by designers, service specialists and managers of enterprises operating complex hydraulic equipment.

Keywords: hydraulic cylinder, sealing elements, service life, wear resistance, polyurethane, PTFE, rod refurbishment, heavy machinery, parameter optimization, tribology

Introduction

Hydraulic systems constitute an indispensable foundation of modern construction, road, mining and specialized machinery. According to the analysis of MRFR, the volume of the hydraulic cylinder market in 2023 was estimated at 5,65 (billion US dollars). It is expected that the hydraulic cylinder market will increase from 5,88 (billion US dollars) in 2024 to 9,2 (billion US dollars) by 2035. It is anticipated that the compound annual growth rate (CAGR) of the hydraulic cylinder market will amount to approximately 4,15 % during the forecast period (2025–2035 years [1]. Such scale and growth dynamics underscore the critical importance of the reliability and durability of hydraulic components for the global economy. At the center of any hydraulic system lies the hydraulic cylinder, whose operational characteristics and maintenance costs depend directly on its failure-free performance. Seals of hydraulic cylinders represent the most vulnerable link: their failure causes internal and external leakage of the working fluid, pressure drop, loss of positioning accuracy and ultimately renders the assembly inoperative.

Practical relevance of increasing the resource of seals is illustrated by the example of modernization of a Caterpillar CAT-320D crawler excavator for demolition works, where a two-line proportional hydraulic system with a medium-pressure line was implemented. Such an upgrade, increasing the machine's functionality and its cost by 15–20 %, simultaneously complicates the operating modes of the hydraulics, which exacerbates the requirements for the reliability of all its components, first and foremost sealing elements that withstand variable loads from attachments (hydraulic shears, concrete crushers).

There is a scientific gap: most studies focus either on investigation of the tribological properties of specific seal materials or on mathematical modeling of their behavior under ideal conditions. There are insufficient works proposing a comprehensive approach that would link the choice of material and the geometry of the seal with real operational factors (contamination of the working fluid, dynamic loads, temperature fluctuations) while simultaneously taking into account advanced technologies for restoration of worn surfaces of rods and cylinders.

The objective of the study consists in proposing and substantiating a methodology for the selection and optimization of seals capable of increasing wear resistance and, as a consequence, extending the overall service life of the hydraulic cylinder.

The scientific novelty of the work lies in proposing a comprehensive approach that combines selection of the optimal seal material, its geometric configuration and parameters of the mating surfaces with advanced restoration technologies, which ensures maximal extension of the hydraulic cylinder life cycle.

The research hypothesis is that optimization of the choice of sealing elements on the basis of analysis of operating conditions and condition of the mating surfaces in combination with the application of modern restoration technologies will make it possible to increase the inter-repair interval of the hydraulic cylinder compared to standard repair procedures.

Materials and Methods

In the literature on increasing the service life of hydraulic cylinders by optimizing sealing-element parameters five main thematic directions can be identified.

The first direction is associated with market analysis, technical requirements and maintenance methods for hydraulic systems. In the Market Research Future report key application segments of hydraulic cylinders, typical designs and their projected development until 2035 are considered [1], and in the hydraulic-oil cleaning manual the influence of working-fluid quality on seal service life and the necessity of regular cleanliness monitoring are emphasized [11]. Both sources stress that improving the seals alone is insufficient for extending hydraulic-cylinder life: it is critically important to ensure optimal operating conditions and timely maintenance.

The second direction covers the development of new composite materials for sealing elements. Daneshmand H., Eskandari M. J., Araghchi M. [2] study reinforced PTFE composites with Inconel 625 powder, combining experimental structural investigations and molecular-dynamics modeling to assess wear resistance. Zhang Y. Y. et al. [4] investigate the tribological behavior of a short-fiber PEEU composite under aqueous lubrication, demonstrating a significant reduction in friction coefficient at optimal fiber content. Huang J. et al. [5] demonstrate a synergistic effect of a three-dimensional hybrid CNT/g-C_3N_4/MoS_2 nanocomposite as an additive to paraffinic oil, leading to improved antiwear performance. These works share a focus on identifying novel polymer–nanomaterial combinations to reduce wear under high load and minimize leakage.

The third direction comprises experimental investigations of the tribological characteristics of conventional seals. Wang B. et al. [3] conduct experiments on the influence of rod surface roughness on sealing-ring lubrication regimes, revealing optimal surface-treatment parameters for reducing friction and wear. Pan Q. et al. [7] compare friction coefficients of double-acting hydraulic cylinders with different reciprocating-seal designs, identifying the most effective geometric and material solutions. Both studies emphasize the critical role of mating-surface condition and precise clearance fitting.

The fourth direction involves reliability studies and failure analysis. Chai L. et al. [6] apply a statistical approach to analyze dynamic sealing performance during drilling operations, identifying factors that reduce seal effectiveness. Walgern J. et al. [9] compare the reliability of electrical and hydraulic blade-pitch-control systems in wind-energy installations using field data, noting high sensitivity of hydraulics to contamination and temperature fluctuations. Odeyar P. et al. [10] review failure-analysis methods for heavy equipment, including FMEA and hydraulic-system failure statistics in mining applications. Li S. et al. [13] analyze failures of metalworking-machine hydraulic systems using incomplete data, demonstrating the effectiveness of Bayesian methods for modeling hazardous operating modes. Collectively, these works underscore that seal reliability is inseparable from overall hydraulic-system reliability and demands a comprehensive diagnostic approach.

The fifth direction is devoted to technological improvements and surface preparation. Chen X. et al. [8] investigate key technologies for increasing the response speed of servo-hydraulic cylinders, including optimization of flow channels and oil-flow control. Zhetessova G. et al. [12] show that abrasive-jet treatment of rods prior to thermal-spray coating significantly improves coating adhesion and wear resistance. Lovrec D., Tič V. [14] analyze methods for determining compatibility of sealing materials with ionic hydraulic fluids, noting insufficient standardization of testing procedures and variability of results depending on methodology [14].

Thus, existing research spans a broad spectrum of approaches, from macro- and microstructural modifications of materials and surfaces to systemic reliability analysis and economic forecasting. A promising direction appears to be conducting comprehensive multifactorial tests of dynamic seals in smart hydraulic systems taking into account material aging and variability of operating parameters.

Results and Discussion

On the basis of study of theoretical data and generalization of practical information proposed an integrated methodology for extending the service life of hydraulic cylinders by means of targeted optimization of sealing element parameters and the condition of mating surfaces. It is based on three interrelated stages: diagnosis and analysis of operating conditions, selection of the optimal sealing solution and application of modern surface restoration technologies.

The first stage performed diagnosis and analysis of operating conditions. The long service life of the sealing assembly is determined by a complex of factors requiring thorough evaluation before repair or modernization. These include operating pressures (nominal and peak), which generate contact stresses and determine the risk of extrusion of the sealing material; temperature regime of the hydraulic fluid, affecting oil viscosity and the physico-mechanical characteristics of the seal (hardness, elasticity); rod stroke speed, defining the friction regime (hydrodynamic or boundary) and the amount of heat generation; composition and quality of the working medium — presence of moisture, chemical aggressiveness and especially the degree of contamination by solid particles (cleanliness class according to ISO 4406); as well as the condition of the rod and barrel surfaces, including roughness, presence of scratches, scoring, corrosion and wear of the chrome coating [6, 9].

Standard factory seals of Komatsu PC8000 excavator hydraulic cylinders, designed for nominal regimes, do not withstand peak loads and the abrasive action of rock dust, which leads to failures at an operating time 2–3 times lower than that declared by the manufacturer. Analysis of failed seals revealed predominant abrasive wear and extrusion of polymer material into the enlarged clearance due to wear of guiding elements.

The second stage follows the selection of the optimal sealing solution. In this case the choice of material and seal design is carried out based on the results of stage 1. In hydraulic drives the most widely used are

- polyurethane (PU) seals, distinguished by high wear resistance, tensile strength and elasticity, but possessing a narrow operating range (–35 °C…+110 °C) and vulnerable to hydrolysis in water-emulsion systems [8, 11].

- PTFE composites, exhibiting an extremely low coefficient of friction, a wide temperature range (–200 °C…+260 °C) and chemical inertness. Since pure PTFE is prone to cold flow, filled compositions are used in hydraulic systems

1) PTFE + bronze (40–60 %) to enhance thermal conductivity and wear resistance at high pressures and speeds.

2) PTFE + carbon/graphite to minimize friction and resist wear under insufficient lubrication.

3) PTFE + fiberglass, increasing stiffness and extrusion resistance, but capable of intensifying abrasive action on mating metal surfaces.

Comparative tests demonstrated a sharp decrease in wear resistance of PU seals with increasing temperature, whereas PTFE composites maintain stable properties over a wider range (see Fig. 1).

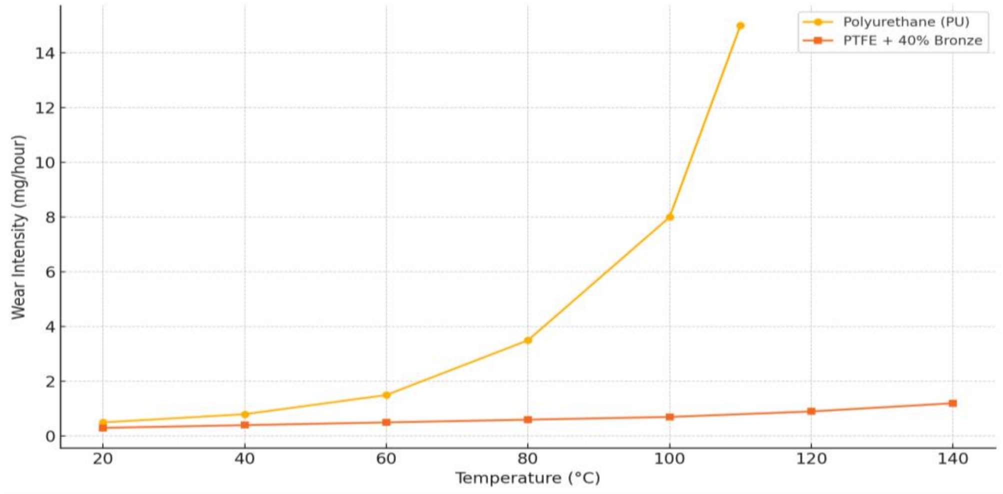

Fig. 1. Dependence of the intensity of seal wear on temperature (compiled by the author based on [3. 5, 10]).

At the third stage should be applied modern surface restoration technologies. The structural arrangement of the sealing assembly of the hydraulic cylinder is of decisive importance for ensuring its tightness and durability under extreme operating conditions. In such cases it is advisable to use a multicomponent sealing system (see Figure 2), including:

● Primary seal (Primary Seal) — typically a wear-resistant PTFE-based composite, performs the main sealing function and provides a reliable barrier against leaks.

● Energizer (Energizer) — a rubber O-ring that creates the necessary preload of the primary seal, thus guaranteeing constant contact with the working surfaces.

● Backup rings (Backup Rings) — rigid inserts that prevent extrusion of the primary sealing material into the clearance at high pressure.

● Guide/wear rings (Guide/Wear Rings) — elements that center the rod and piston, bear the loads, and prevent metal-to-metal friction.

● Wiper/scraper (Wiper/Scraper) — installed on the front cap of the cylinder and serves as a primary barrier, preventing abrasive particles, dust, and moisture from entering the system.

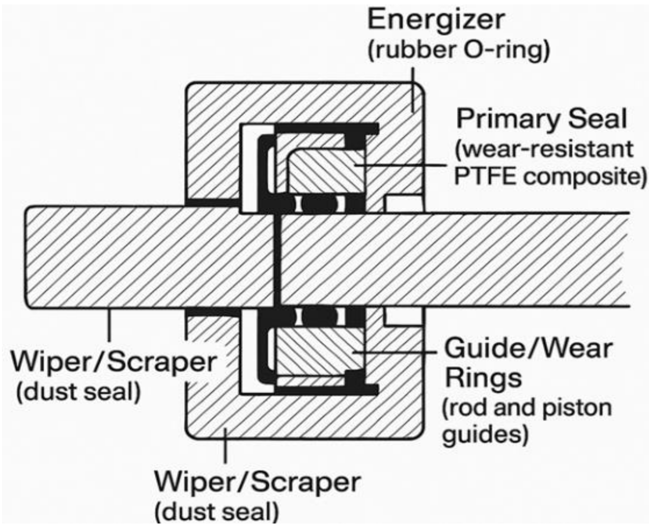

Fig. 2. Schematic diagram of a multi-component rod seal for heavy duty applications (compiled by the author based on [2, 4, 7, 10]).

Next, the features of technologies for the restoration of mating surfaces are considered. In this case, any seal, no matter how perfect, loses effectiveness in the presence of damage on the mating surface. Traditional chrome plating of rods provides a hardness of approximately 60–65 HRC; however, due to brittleness, low impact toughness and susceptibility to corrosion, such a layer proves to be short-lived. Replacement of the worn chrome coating with a ceramic one improves the operational characteristics of the assembly. By means of plasma or detonation spraying, a layer based on aluminum oxide (Al_2O_3) or chromium oxide (Cr_2O_3) is formed, which after grinding and polishing achieves a hardness of up to 70–75 HRC, possesses chemical inertness, prevents adhesion of contaminants and, thanks to its porous structure, retains lubricant, thereby improving the operating conditions of the seal [8, 13].

The dependence of seal life on the roughness of the mating surface exhibits a pronounced nonlinear character: at Ra < 0.1 μm a lubricating film does not form, resulting in dry friction and accelerated wear, whereas at Ra ≈ 0.4 μm the surface acts as an abrasive, which also leads to rapid seal failure. Analysis of numerous tests has shown that for most sealing systems the optimal range of Ra lies between 0.16 and 0.32 μm [3].

Table 1 presents a description of the comparative efficiency of existing rod restoration technologies.

Table 1. Comparative efficiency of rod restoration technologies (compiled by the author based on [3, 12, 14]).

Restoration technology	Coating hardness, HRC	Relative wear resistance	Corrosion resistance	Approximate cost (relative to a new rod)
Re-chroming	60-65	1.0 (base)	Satisfactory	40-50%
Gas-thermal spraying (iron-nickel alloy)	58-62	1.2-1.5	Good	50-60%
Plasma spraying (Al_2O_3/TiO_2 ceramic)	70-75	3.0-5.0	Excellent	70-85%
Laser cladding	55-65	1.5-2.0	Good	65-80%

Practical implementation of the integrated technical solution demonstrated an effect of optimization of service life and costs. In particular, for Komatsu PC8000 hydraulic cylinders the introduction of bronze-filled PTFE seals in combination with piston rods refurbished by ceramic coating provided an increase in the interval between overhauls by 2,5–3 times, which led to a noticeable reduction in operating expenses and equipment downtime.

A similar economic effect is confirmed by the experience of FixRent in the restoration of cast iron swivel trolleys for JCB and CAT machines. Instead of the standard replacement of the assembly costing approximately 5000 € with a waiting period of up to one and a half months, a method of overlay welding and subsequent boring of the seating holes was employed. This approach enabled reduction of repair time to three days and reduction of costs to approximately 1000 €, which provided client cost savings and minimization of equipment downtime.

Results of the conducted study demonstrate that replacing the traditional algorithm of direct substitution of a worn seal with an identical counterpart by a comprehensive methodology incorporating multifactorial analysis of operating conditions and the application of modern technological solutions ensures a multiple extension of hydraulic cylinder service life. This approach not only optimizes direct expenditures on spare parts and repairs but also, and notably, reduces indirect losses associated with forced downtime of expensive equipment.

Conclusion

The conducted study enabled the development and theoretical substantiation of an integrated methodology for extending the service life of hydraulic cylinders, implementing a systemic approach to the selection and adjustment of sealing element parameters. Within the scope of the work a systematization of the primary operational factors influencing seal durability was carried out. A comparative analysis of contemporary sealing materials was performed and their suitability assessed under various aggressive and extreme conditions. The role of the condition of mating surfaces and highly effective restoration technologies was demonstrated.

The main conclusion of the study is that the maximum increase in hydraulic cylinder service life is achieved not through a single optimal seal but through the synergistic interaction of three complementary components: firstly, the seal material and design must correspond to actual rather than nominal operating regimes (taking into account peak pressures, temperature fluctuations and contamination levels of the medium); secondly, the condition of mating parts (rod and barrel) must ensure not only low roughness but also increased hardness and wear resistance of the restoration coating; thirdly, the geometric and functional configuration of the entire sealing assembly, including guide elements, support rings and wipers, must reliably protect the primary seal and maintain system operational stability.

The proposed hypothesis is confirmed: application of the proposed algorithm, in particular the use of composite PTFE seals in combination with rods restored by ceramic coating, allows more than a twofold increase in the maintenance interval of hydraulic cylinders under severe operating conditions. Examples of mining equipment hydraulic cylinder repairs and restoration of assemblies in construction machinery clearly demonstrate the high technical and economic efficiency of this approach. The proposed algorithm can be implemented by engineering and technical services when planning scheduled overhauls and modernizing hydraulic systems, thereby ensuring significant reduction of operating costs and enhancement of equipment reliability.

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