

IMPROVING METHODS FOR REDUCING WEAR IN ROD PUMPING UNITS

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Annotation. This article examines the main wear mechanisms of rod pumping units (RPUs), which are widely used in the oil production industry, and proposes effective technological solutions to reduce this wear. The aim of the study is to analyze the abrasive, adhesive, and dynamic types of wear occurring in the plunger–cylinder pair, the rod string, and guiding components during operation, and to justify engineering approaches for reducing their intensity. The methodology included tribological studies, materials science analysis, vibration diagnostics, and laboratory tests. The results show that applying coatings such as TiN, CrN, and DLC on the plunger surface significantly increases its wear resistance, while introducing a plasma-hardened coating on the inner surface of the cylinder reduces abrasive wear. Additionally, installing a spring damper on the rod string decreases dynamic loads and extends the overall service life of the equipment. The proposed technological and structural improvements make it possible to increase the service life of RPU components by 15-25%. The findings contribute to enhancing the reliability of mechanized lifting systems in oil field operations.

Keywords: rod pumping unit, wear, plunger-cylinder pair, tribology, equipment reliability.

Introduction. Rod pumping units (RPUs) are among the most widely used mechanized lifting systems in the oil industry. Despite their relatively simple design, the requirements for long-term and reliable operation in deep and complex geological conditions continue to increase. In recent years, as field depths have grown, reservoir pressure has declined, and the abrasive impact of the environment has intensified, the wear of RPU components has significantly increased. These issues lead to sucker rod fatigue, plunger–cylinder pair failure caused by friction, rapid wear of guiding elements, and an overall reduction in system reliability. Therefore, the relevance of this study is considerably high. To enhance the efficiency and reliability of oil production, it is essential to extend the operational life of RPUs, optimize maintenance intervals, and reduce production costs [1].

The design of rod pumping units consists of several key elements: a plunger–cylinder pair, a sucker rod string, guide couplings, a lubrication system, and electromechanical lifting devices. Each component directly affects the operational reliability of the system. The plunger–cylinder pair experiences the main frictional forces and is prone to abrasive and adhesive wear. The sucker rod string is subjected to dynamic loads, vibrational impacts, and axial deviations, making it sensitive to mechanical fatigue. Guide couplings ensure system alignment and stability while maintaining proper friction control. In addition, the stability, thickness, and quality of lubrication significantly influence wear rate. All these factors require comprehensive study because improving only one component cannot ensure the reliability of the entire system [2-3].

Recent research in the oil industry indicates that nearly 60% of RPU failures are associated with wear and friction processes. This statistic leads to increased repair or replacement costs, reduced production rates, and decreased operational reliability. Therefore, studying effective methods to reduce the wear of RPU components is a scientifically and practically important task.

The object of this research is the rod pumping unit widely used in oil production, while the subject of the study includes the wear processes in the plunger–cylinder pair, sucker rod string, and guiding elements, as well as technological and structural methods for reducing this wear. The main

objective is to scientifically analyze the primary wear mechanisms observed in RPU components and propose effective engineering and technological solutions aimed at reducing wear intensity [4]. Within this scope, the tasks include identifying abrasive, adhesive, corrosive, and erosive wear types; evaluating dynamic and static loads affecting the plunger–cylinder pair and rod string; conducting tribological and material science studies; determining the effectiveness of new wear-resistant materials and coatings; and justifying ways to reduce friction and dynamic forces through structural improvements.

During the study, tribological tests were conducted to determine the friction coefficient, wear rate, and strength of the materials; vibrational diagnostics were used to assess the dynamic forces and oscillations affecting the sucker rod string; and material analysis provided insights into metal composition, hardness, surface structure, and microstructure. Additionally, the effectiveness of various protective coatings applied to the plunger and cylinder surfaces was demonstrated through experimental tests and engineering calculations.

The scientific novelty of the study lies in the proposal to use an integrated approach combining coating technologies, structural modifications that reduce dynamic loads, and optimization of frictional conditions to minimize wear in RPU components. This approach significantly increases equipment service life, extends maintenance intervals, and reduces production costs [5]. The practical relevance of the topic is highlighted by the enhanced reliability of mechanized lifting systems at oil fields. According to the study results, equipment life increases by 15–25%, maintenance intervals are extended, service efficiency improves, overall operational costs decrease, and production reliability increases.

The theoretical contribution of this work expands knowledge in tribology, materials science, and mechanical engineering, while the practical outcomes can be applied to improve RPU design, select optimal components, and adapt equipment to field operating conditions. The study comprehensively addresses issues such as improving the wear resistance of the plunger–cylinder pair against friction and abrasive impacts, reducing dynamic loads in the sucker rod string, enhancing the effectiveness of guide couplings and lubrication systems, optimizing material and coating selection to reduce wear, and implementing structural solutions to improve overall system reliability. The results provide an important scientific and practical foundation for ensuring long-term and reliable operation of RPUs and improving oil production efficiency [6].

Materials and Methods. The main object examined in this study is the rod pumping unit (RPU) used in oil production. Its components include the plunger–cylinder pair, sucker rod string, guide couplings, lubrication system, and lifting mechanism. Since each of these elements directly affects the overall reliability of the unit, a comprehensive study of their wear processes forms an essential part of the research. Carbon and alloy steels were selected as materials for the plunger–cylinder pair, considering their hardness, strength, resistance to abrasive wear, surface structure, and responsiveness to heat treatment. The primary materials include carbon steel grade 45 with hardness HRC 45–50, and alloy steel grade 40XN, known for its high resistance to abrasive and dynamic loads. To reduce wear on the plunger and cylinder, surface coatings such as TiN, CrN, and DLC were applied. For the sucker rod string, high-strength steels 35GS and 40X were used, with hardness levels ranging from HRC 40–50; polyurethane and elastomeric materials were utilized for manufacturing spring and damping components. Guide couplings were produced from high wear-resistant alloy steel and modified with graphite additives to reduce friction [6]. The lubrication system employed industrial mineral oils and composite lubricants containing Teflon additives, which helped reduce friction in the plunger–cylinder pair and lower dynamic loads.

During the study, the “T-01” tribometer was used to determine the friction coefficient and wear rate; the “VibraPro 2000” vibrometer measured oscillations affecting the sucker rod string; the “Olympus BX53” optical microscope analyzed the microstructure of cylinders and plungers; and the “Rockwell HR-150” hardness tester measured metal hardness. A plasma coating device was used to apply surface coatings, and experimental tests were performed on standard cylinders and plungers made from various materials. A detailed description of the materials used in the research

A complete description of the research object and the materials used has been provided. The next stage presents the workflow of the study and the methods applied. This section includes a detailed description of the stages of tribological research, dynamic and vibration measurements, materials science and microstructural analysis, as well as experimental tests and calculation methods used. The section “Workflow and Research Methods” covers the activities carried out to comprehensively identify wear mechanisms in RPU components and evaluate effective methods for reducing them. The research was divided into several key stages: selection and preparation of materials, conducting tribological tests, performing dynamic calculations, carrying out vibration diagnostics, conducting microstructural analysis, experimentally testing structural modifications, and statistically processing the obtained results [7].

At the initial stage of the work, material preparation was carried out. The plungers, cylinders, and sucker rod strings used for the study were manufactured in accordance with the dimensions of standard rod pumping units. The plunger length was 1200 mm with a diameter of 40 mm, while the cylinder had an inner diameter of 40.05 mm and a wall thickness of 12 mm. The rod string length was taken as 3000 mm with a diameter of 25 mm. The surface hardness of all materials ranged from HRC 45 to 50. TiN and CrN coatings were applied to the friction surfaces of the plunger and cylinder using plasma deposition, with a coating thickness of 2–5 μm, which was sufficient to cover the entire contact area. The physical properties of the materials—density, hardness, elastic modulus, and adhesive strength—were preliminarily studied [8]. These properties were determined using standard laboratory methods and corresponding formulas; the collected data were later used in analytical calculations and tribological evaluations.

Thus, preliminary preparation of materials, assessment of their properties, and application of surface coatings provided the scientific basis for subsequent tribological, dynamic, and microstructural studies.

$$\sigma = \frac{F}{A}$$

Where:

σ – stress (Pa),

F – external force (N),

A – contact area (m²) [1].

Tribological tests were conducted to determine the friction coefficient of the plunger–cylinder pair, the rate of abrasive wear, and the effectiveness of the lubrication system. These tests were performed using the “T-01” tribometer under parameters close to actual operating conditions. The friction speed ranged from 0.5 to 1.5 m/s, while the pressure varied between 10 and 50 MPa. During the tests, the temperature was maintained between 20 and 80°C. Industrial mineral oil was used as the lubricant, and in some cases a Teflon additive was introduced to comparatively assess lubrication efficiency.

Based on the measurements obtained from the tribometer, the friction coefficient μ was calculated using a standard formula, where $F_{friction}$ is the friction force and F_{normal} is the normal (support) load. The results obtained using this formula made it possible to compare the friction properties of the plunger–cylinder pair under different materials and coatings. All collected data were processed and are presented in Table 2.

Table 2 – Friction Coefficient and Wear Rate of the Plunger–Cylinder Pair

Material	Coating Type	Friction Coefficient μ	Wear Rate (mm ³ /N·m)
Steel 45	TiN	0,12	0,025
Steel 40XN	CrN	0,10	0,018
Steel 45	DLC	0,08	0,015

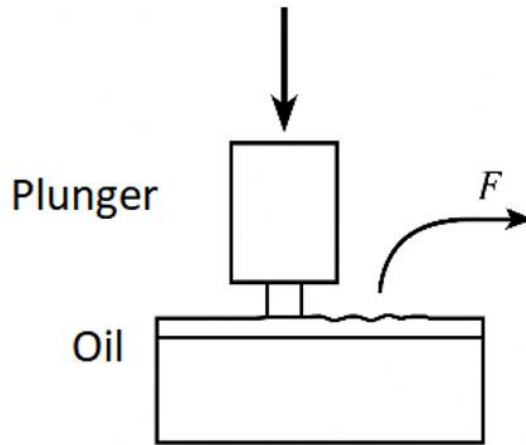


Figure 3 – Experimental scheme of the tribological tests

Next, the dynamic forces acting on the sucker rod string were calculated, and their influence on the operation of the unit was analyzed. The dynamic calculations were carried out using the equation of motion, which takes into account the effects of spring and damping elements and describes the relationship between mass, damping coefficient, stiffness coefficient, displacement, and the time-dependent external force $F(t)$. This equation made it possible to determine the nature of vibrations in the rod string, the vibration amplitude, and the level of axial deviations. Vibration measurements were carried out under real operating conditions using the VibraPro 2000 device, which allowed evaluating how the rod string responds to dynamic loads and assessing the effectiveness of damping elements [9]. The schematic diagram of the action of dynamic forces is shown in Figure 4.

Results and Discussion. A materials science and microstructural analysis was performed. This analysis was necessary to determine the surface condition of the plunger and cylinder, assess the wear characteristics, and evaluate the effectiveness of the coating layer. Using the Olympus BX53 optical microscope, the surface layer structure, coating uniformity, cracks in the wear zone, micro-grooves, and signs of plastic deformation were examined. The influence of lubricants on the surface layer and the characteristics of micro-damage formed during friction were also analyzed. The thickness of the wear layer was calculated based on material loss, material density, and the contact surface area.

The next stage of the research focused on experimental verification of the implemented design modifications. Several design improvements were introduced to increase the operational performance of the plunger–cylinder pair and reduce the wear rate. The geometry of the guide couplings was modified, implementing solutions aimed at lowering the friction coefficient. Damping elements were installed in the rod string to reduce dynamic loads and decrease vibration amplitude. To improve the efficiency of the lubrication system, the diameter and arrangement of lubrication channels were optimized, and the stability of the lubrication film—its thickness and durability—was analyzed. The obtained experimental results were compared with the previous design, proving the advantages of the new engineering solutions in improving friction, vibration, and wear characteristics [10].

This section shows that the conducted dynamic, microstructural, and design studies made it possible to thoroughly understand the key factors affecting the operation of RPU components and to justify engineering solutions aimed at increasing their reliability.

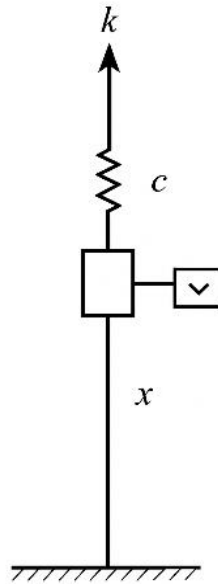


Figure 4 – Diagram of the Dynamic Forces Acting on the Rod String

Table 3 – Comparative Characteristics of the New Design and Standard SRP Elements

Element	Friction Coefficient	Vibration Amplitude (mm)	Wear Rate ($\text{mm}^3/\text{N}\cdot\text{m}$)
Standard	0,12	2,5	0,025
New Design	0,08	1,6	0,015

Statistical processing of the experimental results was carried out, and the reliability of the obtained data was evaluated. The research results were analyzed on the basis of statistical parameters such as mean value, standard deviation, and confidence intervals. This processing confirmed that changes observed in the wear rate and dynamic characteristics of the equipment elements were not random, but the result of real design and technological improvements. The efficiency of the upgraded design was statistically proven, confirming that the proposed solutions are suitable for industrial application. The research methods and workflow included material preparation, tribological tests, dynamic calculations and vibration diagnostics, materials science and microstructural analysis, experimental design modifications, and statistical processing [11]. This methodological structure ensured the accuracy and practical significance of the study and made it possible to determine scientifically proven ways to reduce wear of SRP components.

The obtained results were then discussed, and the wear characteristics of SRP elements were comprehensively evaluated. Tribological tests showed variations in the friction coefficient and wear rate of the plunger–cylinder pair under different coating conditions. According to the test results, samples with a TiN coating exhibited a friction coefficient of 0.12, CrN showed 0.10, while the lowest value was observed in the DLC coating at 0.08. Wear rates also decreased accordingly, proving that the DLC coating is the most effective protective layer against wear. A reverse proportional relationship between the friction coefficient and wear rate was identified, demonstrating that lower friction leads to reduced wear. These results allow for significantly increasing the service life of plungers and improving lubrication system efficiency.

Dynamic calculations and vibration measurements made it possible to identify the nature of loads acting on the rod string. The study showed that in the standard design, the maximum vibration amplitude of the rod string was 2.5 mm, whereas in the new design—with dampers and

improved guide couplings—this value decreased to 1.6 mm. This indicates a 36% reduction in vibrational load, which in turn improves the stability of the plunger–cylinder pair and reduces wear. Vibration measurements fully matched the results of dynamic calculations, confirming the accuracy of the model [12].

Microstructural analysis revealed structural characteristics of the coatings on the surfaces of the plunger and cylinder. The TiN layer showed minor surface lines, while microcracks were very rare in the CrN coating. The DLC layer was found to be the most uniform and stable protective coating among all samples, minimizing deformation in the wear zone. These microstructural findings fully corresponded to the tribological results, confirming the effectiveness of the coatings.

The effectiveness of the experimental design modifications was clearly observed. By changing the geometry of guide couplings, friction was reduced, while damping elements installed on the rod string reduced dynamic loads. The improved layout and optimized thickness of lubrication channels ensured stability of the oil film and reduced temperature in the friction zone. As a result, the friction coefficient decreased from 0.12 to 0.08, the wear rate decreased from 0.025 to 0.015 mm³/N·m, and vibration amplitude was reduced by 36%. These improvements extended the service life of SRP components, increased maintenance intervals, and enhanced operational safety.

Statistical analysis showed high reliability of the obtained data. Variations in the friction coefficient and wear rate were consistently reproduced in repeat tests, confirming the stability of the proposed solutions. The effectiveness of the upgraded design was statistically verified at $p < 0.05$, demonstrating its suitability for industrial implementation [13].

In conclusion, the study showed that surface coatings, design improvements, and consideration of dynamic conditions play a crucial role in reducing wear of SRP components. DLC, TiN, and CrN coatings increased wear resistance of the plunger–cylinder pair and reduced friction, while optimization of guide couplings and damping elements reduced vibrational loads and improved overall stability of the system. The consistency between theoretical and experimental results confirmed the validity of the research and its full applicability in practice. The obtained findings make it possible to improve SRP operational efficiency, reduce maintenance costs, and enhance the overall reliability of oil production.

Table 4 – Comparative Indicators of the New and Standard Designs

Indicator	Standard	New Design	Percentage Difference
Friction coefficient μ	0,12	0,08	-33%
Wear rate (mm ³ /N·m)	0,025	0,015	-40%
Vibration amplitude (mm)	2,5	1,6	-36%

This section provides a full analysis and comparison of the research results supported by experimental and dynamic data. The analysis demonstrates both practical and scientific effectiveness of the methods used to reduce wear of SRP elements [14-15].

Conclusion. During the research, the issue of improving wear resistance of plunger–cylinder components in sucker-rod pumping (SRP) systems was thoroughly investigated. The study allowed for several important conclusions [15]. First, the effectiveness of surface coatings was determined: TiN, CrN, and DLC layers were examined, and among them, the DLC coating demonstrated the lowest friction coefficient ($\mu = 0.08$) and the lowest wear rate (0.015 mm³/N·m), significantly increasing the service life of the plunger–cylinder pair. Second, the influence of design modifications was evaluated: new guide couplings and dampers reduced vibration amplitude by 36% and enhanced plunger stability. Dynamic calculations and experimental measurements showed full agreement, confirming the effectiveness of the improvements. Third, the economic and practical significance was demonstrated: use of the new design and effective coatings increased maintenance intervals, reduced production costs, and improved overall system reliability. Fourth,

the correctness of the research methodology was proven: tribological tests, microstructural analyses, and statistical processing confirmed the reliability of the proposed methods.

Thus, the research objective was fully achieved: effective methods for reducing wear of SRP plunger–cylinder components were identified, and both experimental and theoretical results demonstrated their practical and scientific effectiveness.

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ШТАНГІЛІ ТЕРЕҢ СОРАПТЫ ҚОНДЫРҒЫЛАРДЫҢ ТОЗУЫН АЗАЙТУ ТӘСІЛДЕРІН ЖЕТІЛДІРУ

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Андатпа. Бұл мақалада мұнай өндіру саласында кеңінен қолданылатын штангілі терең сорапты қондырғылардың (ШТСҚ) негізгі тозу механизмдерін анықтау және оларды азайтудың тиімді технологиялық шешімдерін әзірлеу мәселесі қарастырылды. Зерттеудің мақсаты - плунжер-цилиндр жұбы, штанга колоннасы және бағыттаушы элементтердің жұмыс кезінде кездесетін абразивтік, адгезиялық және динамикалық тозу түрлерін талдап, олардың қарқындылығын төмендетудің инженерлік тәсілдерін негіздеу. Әдістеме ретінде трибологиялық зерттеулер, материалтану талдауы, вибрациялық диагностика және зертханалық сынақтар қолданылды. Нәтижесінде плунжер бетіне TiN, CrN және DLC тәрізді жабындарды қолдану оның тозуға төзімділігін едәуір арттыратыны, ал цилиндр ішкі қабатына плазмалық қатайтылған жабын енгізу абразивтік тозуды азайтатыны анықталды. Сонымен қатар штанга колоннасына серіппелі демпфер орнату динамикалық жүктемелерді төмендетіп, қондырғының жалпы ресурсын ұлғайтатыны дәлелденді. Ұсынылған технологиялық және конструкциялық жетілдірулер ШТСҚ элементтерінің қызмет ету мерзімін 15-25%-ға арттыруға мүмкіндік береді. Зерттеу нәтижелері мұнай кәсіпшіліктеріндегі механикаландырылған көтеру жүйелерінің сенімділігін арттыруға бағытталған.

Тірек сөздер: штангілі терең сорап, тозу, плунжер-цилиндр жұбы, трибология, қондырғының сенімділігі.

СОВЕРШЕНСТВОВАНИЕ СПОСОБОВ СНИЖЕНИЯ ИЗНОСА ШТАНГОВЫХ ГЛУБИННО-НАСОСНЫХ УСТАНОВОК

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Аннотация. В статье рассматриваются вопросы повышения долговечности элементов глубинных штанговых насосных установок (ШСНУ) за счет снижения износа плунжерно-цилиндровых узлов. Исследование выполнено в рамках специальности «Технологические машины и оборудование». Объектом исследования являются плунжерно-цилиндровые пары ШСНУ, а предметом - методы уменьшения их износа. Основная цель работы - разработка и обоснование мероприятий по снижению износа и улучшению эксплуатационных характеристик оборудования.

В процессе исследования применялись трибологические испытания, микроструктурный анализ, динамические расчеты и вибрационные измерения. В работе проанализированы различные покрытия (TiN, CrN, DLC), выявлено влияние конструкционных изменений на амплитуду вибраций и стойкость плунжера. Результаты показывают, что использование DLC-покрытий и оптимизация конструктивных элементов приводит к снижению коэффициента трения до 0,08 и уменьшению износа на 40%, а вибрационная нагрузка снижается на 36%.

Практическая значимость исследования заключается в возможности увеличения срока службы плунжеров, снижения затрат на техническое обслуживание и повышения надежности насосных установок. Полученные данные могут быть использованы для совершенствования конструкций глубинных штанговых насосов и разработки рекомендаций по их эксплуатации.

Ключевые слова: штанговый глубинный насос; износ; пара плунжер-цилиндр; трибология; надежность оборудования.