ABSTRACT

of the dissertation work of Olga Vladimirovna Ivanova
"Development of constructive and technological solutions to increase the life of rod depth pumps", submitted for the degree of Doctor of Philosophy (PhD) in the educational program 8D07101 – "Mechanical Engineering"

The relevance of the work. Mechanical engineering is the basic system-forming branch of the economy of any industrially developed state. This industry ensures the technological stability of key sectors of the economy – energy, mining, metallurgical and agro-industrial complexes, construction and transport industries. Mechanical engineering has a high multiplicative effect on related industries, creates demand for highly productive services, being one of the most innovative industries, contributes to the complexity of manufactured products, a steady increase in export revenues, and as a result, replenishment of the state budget, technological progress and overall improvement in the quality of life of the population.

One of the key roles in mechanical engineering is played by the oil and gas complex of the state. The oil and gas complex of Kazakhstan plays a leading role in the economic development of the country and occupies one of the leading positions in the global oil and gas production market. According to the U.S. Energy Information Administration, Kazakhstan ranks 17th among the countries in the world in terms of oil production. Kazakhstan's engineering industry covers 10 types of economic activity in the country. One of the main directions in mechanical engineering is the production of equipment and spare parts for machines and enterprises of the oil and gas industry, for example, such as pumping equipment, rocking machines, shut-off valves, oil and gas filtration equipment, etc.

There are about 200 active oil and gas fields in Kazakhstan, of which 50% are fields located at a late stage of development (with a flow rate of less than 40 m^3/day), which are operated by rod depth pumps.

The average annual demand of national companies for new pumps is 70% of the current fund. Despite the reliability and peculiarity of using rod depth pump in low–flow wells, complicating working conditions lead to pump failure before the established resource (350 days) instead of 570-600 days. rod depth pump failures account for more than 34% of the total number of failures of other types of pumps. The oil industry of Kazakhstan is one of the most important sectors of the economy of Kazakhstan. With the high dynamics of the reduction of world oil reserves, the issue of increasing the volume of its production currently does not lose its relevance.

Thus, oil-producing enterprises face a scientific and practical problem associated with increasing hydrocarbon production not only through exploration and development of new fields, but also through the improvement and creation of new energy-efficient pumping complexes with high resource durability and their use in fields with small and medium-capacity wells, which confirms the relevance of research.

Leading Kazakhstani and foreign scientists Agamirzoev D.I., Adonin A.N., Alexandrov P.O., Aliverdizade K.S., Arbuzov V.N., Bakhtizin R.N., Beketov S.B., Burov A.E., Valeev M.D., Virnovsky A.S., Voskoboynikov A.A., Galimullin M.L.,

Greifer V.I., Dolov T.R., Dubinov Y.S., Zalyatov M.M., Ivanovsky V.N., Ismagilov F.G., Ishmurzin A.A., Ishmukhametov B.H., Korshunov V.N., Latypov B.M., Mashkov V.A., Minlikaev V.Z., Muravyev I.M., Pirverdyan A.M., Sultanov B.Z., Topolnikov A.S., Urazakov K.R., Khamitov A.T., Hoang T.N., Yurchuk A.M., Al-Taq A.A., John F. Mabry, Neil Robert Hall, Nielsen Jr William D., D.A. Shock, J.O. Sudbury, J.J. Crockett and many others dealt with the issues of wear research, methods of ensuring resource durability and operability, manufacturing technology and modernization of the main structural elements of downhole rod deep pumps.

The purpose of the design work is to ensure high durability of the oil production pump due to the technology of laser hardening of the internal surfaces of critical parts and to increase its efficiency by developing design solutions in the valve assembly and filtration system.

To achieve this goal, it is necessary to solve the following **tasks:**

- to investigate and justify the criteria for failures of the rod pump, which reduce the efficiency of its performance when exposed to dynamic resistance forces on the wear elements of the plunger-cylinder system.
- to improve the mathematical model of the efficiency and productivity of an oil production pump in dynamic operation;
- to establish the dependence of the wear change on the deviation of the design trajectory of the mated parts relative to the axis of symmetry under alternating dynamic loads;
- on the basis of experimental data, to perform simulation modeling of the dynamic process of the rod deep pump operation, taking into account the influence of various factors on the reliability and operability of the downhole pumping unit;
- to develop a technology for hardening the inner surface of the pump cylinder using highly concentrated laser energy sources;
- to improve the valve mechanism, which provides the effect of damping shock loads.

Research methods. The dissertation work used research methods used in mechanical engineering based on the fundamental principles of basic sciences and production: engineering technology, materials science, structural materials and heat treatment, fundamentals of design and machine parts, mathematical statistics.

Theoretical research was based on the application of methods of the theory of numerical solutions to mathematical problems using simulated 3D modeling. To confirm the reliability of the research results, the 3D simulation process was carried out using the following licensed software products: COMPASS-3D (APM FEM application), SolidWorks (FloEFD application), MatLab. During the experiment, the method of metallographic examination was used.

The object of the study. Downhole rod depth pump for lifting oil fluid from medium and low-flow wells and ways to increase its resource life. The pump operates in conditions complicated by the increased viscosity of oil, a significant content of mechanical impurities, asphalt-resin-paraffin deposits and salts.

The subject of the study. A method for increasing the reliability and resource durability of the wear elements of the cylinder – plunger – valve pair system during operation of a rod depth pump.

The scientific novelty of the dissertation work consists in establishing a causal relationship between the conditions and modes of operation of the pump, its durability from its technological and structural parameters, which is reflected in the following provisions:

- the criteria of failures (δ_t>0.2 mm, q_t>0.5Q_f) of the rod pump are justified, which reduce the efficiency of its operation when exposed to dynamic resistance forces on the wear elements of the plunger-cylinder system;
- improved mathematical model describing the pump supply process (Q_f) when changing the maximum allowable gap $\delta_t=f(i)$ in the plunger-cylinder system of the rod pump and leaks (q_t) due to violation of the kinematics of motion ($\Delta\lambda_\Sigma$) from dynamic loads;
- the effectiveness of the use of a composite material is justified, which ensures the distribution of contact stresses over the area of impact of the locking element in the area of the "conditional meridian" on the seat surface;
- the optimal technological modes of spraying (v_d, l_d, m_h) and power characteristics (P, q, d_l) of the laser installation are substantiated;
- the dependences of changes in the physico-mechanical properties of the hardened surface (Hμ, σ_{cl}) on the deposition thickness (h), distance (l_d) and deposition rate (v_d) have been established, providing qualitative criteria for the manufacture of the cylinder;
- a method for increasing the reliability of the rod depth pump by filtering oil through the introduction of a self-cleaning centrifugal filter with power extraction from oil lifting is substantiated.

Practical significance.

The developed design and manufacturing technology of the locking element of the valve pair "saddle-ball" of the plunger pump, using combined materials, ensure effective fit of the ball to the seat, eliminating leaks, reduce the destruction of the working edge of the seat and allow effective redistribution of shock loads due to the achieved damping effect.

The developed laser technology for manufacturing and hardening the inner surface of the contact pair "plunger-cylinder" of small diameter (44 mm) mining pumps allows to obtain high quality (σ, porosity<7%, K_i) of the hardening surface having optimal values of coating thickness (h), surface microhardness (Hμ), surface layer hardness (61÷65 HRC), complete fusion of powder material, effective fusion of base metal particles with the sprayed surface, to reduce the thermal effect on the base metal and reduce the level of residual deformations and stresses in the pump cylinder.

The developed design of a controlled laser spraying unit allows the coating of multicomponent powder materials to be applied to the inner surface of a long cylinder (up to 6 m) with a small diameter (44 mm) of a downhole rod deep pump, ensuring a continuous and uniform laser spraying process. And the laser pulse

ensures high sputtering quality, adhesive properties and eliminates overheating of the surface in the zone of thermal influence.

The developed design of a self-cleaning centrifugal filter, for which an innovative patent for a utility model of the Republic of Kazakhstan No. 6888 dated 02/25/2022, No. 8, provides a high pump life due to the gravitational effect of lifting and lowering oil and effective purification from mechanical impurities discharged into the bottom of the well. Under the pressure of an oil liquid passed through the holes at an angle (α= 5÷15°) to the filter axis, passing metal blades, ensures the rotation of the filter on the bearing. Under the action of centrifugal force, large suspensions of impurities are retained on the outer walls of the filter, most of which remain in the bottom of the well, and the other part is squeezed out by the same force into the filter holes, which in turn are cleaned with a crown.

The provisions of the dissertation submitted for defense:

- an improved mathematical model describing the pump supply process (Q_f) when the maximum allowable gap $\delta_t=f(i)$ changes in the plunger-cylinder system of the rod pump and leaks (q_t) due to violations of the kinematics of motion ($\Delta\lambda_\Sigma$) from dynamic loads;
- established dependences and effective limits of changes in the physico-mechanical properties of the hardening surface on the technological modes of spraying (v_d, l_d, m_h), taking into account the power characteristics (P, q, d_l) of the laser installation;
- dependences of changes in the adhesive properties of the coating on the power modes of the laser pulse and the hardness of the hardened layer from the distance to the focal plane;
- design and manufacturing technology of the shut-off element of the valve pair "saddle-ball" plunger pump, using combined materials (Steel 20 GOST 2590-88 and composite rubber compound 7B–14MA TC 38-105-1082-86 with a metal-ceramic filler);
- optimal technological modes of spraying (v_d, l_d, m_h) and power characteristics (P, q, d_l) laser installation;
- controlled installation for laser spraying of the inner surface of long cylinders (up to 6 m) of small diameter (44 mm);
- the design of the self-cleaning filter of the rod depth pump.

Approbation of the work.

The main results of the dissertation research are presented and they were tested at international and Kazakhstani scientific and practical conferences and technical seminars: VI International scientific and practical conference of students, postgraduates and young scientists "Fundamental and Applied research of young scientists", SibARA (Omsk, Russia, 02/10/2022, RCIN); International Scientific and Technical Conference "INTERSTROYMECH-2022" (Yaroslavl, Russia, 12-14.10.2022); International scientific and practical conference "Trends in the development of natural and technical sciences in the modern world", Kozybayev University (Petropavlovsk, Kazakhstan, 11/18/2022); technical meeting of engineering and technical staff of Venture Firm Poisk LLP (Petropavlovsk,

10/25/2022); International Conference on Innovative Research "EUROINVENT ICIR 2023", Iasi, 11th-12th of May 2023; scientific internship at Sergo Ordzhonikidze Russian State Geological Exploration University (MGEI) (Moscow, Russian Federation, 10.05.-09.06.2023); Republican scientific and practical seminar "Innovative technologies in mechanical engineering and robotics" (Petropavlovsk, M.Kozybaev SKU, 04/15/2024).

Publications.

The main results of the dissertation work have been published in 13 publications, including 1 article in publications recommended by the National Scientific and Scientific Council of the Republic of Kazakhstan, 4 publications in International scientific conferences, 3 of them in foreign ones; 3 articles in scientific foreign journals included in the scientific citation database Scopus – Q2, 60 (category Materials Science / Surfaces, Coatings and Films and the Materials Science / General Materials Science category); 1 article in The 5th International Conferenceon Green Designand Manufacture indexed in Scopus (CiteScore Scopus percentile over 40); 1 monograph, published by Materials Research Forum LLC Millersville, PA, USA in the series of books Materials Research Foundations; 1 article in a foreign scientific journal. Two innovative patents for a utility model of the Republic of Kazakhstan were obtained (No. 6888 dated 02/25/2022 byul. No. 8; No. 6809 dated 14.01.2022 byul. No. 2) and one act of introduction into production.

Personal contribution of the author.

The main theoretical and experimental results obtained during the dissertation research were obtained by the author independently. In published scientific papers as part of a team of co-authors, the applicant plays a leading role in the generalization and analysis of the results obtained.

The structure of the dissertation.

The dissertation work consists of an introduction, six chapters and a conclusion, a list of sources used and appendices. The work is presented on 185 pages, contains 88 figures, 18 tables and a list of references from 204 titles of publications by domestic and foreign authors.

The results of the study.

To implement technological solutions to increase the service life of the piston pump, the failure criteria (δ_t>0.2 mm, q_t>0.5 Q_f m^3/day) are justified, which reduce the efficiency of its operation when exposed to dynamic resistance forces on the wear elements of the plunger-cylinder system.

The mathematical model of pump performance (Q_f) and its service life has been improved when changing the maximum permissible gap $\delta_t=f(i)$ in the plunger-cylinder system of a rod pump and leaks (qt) due to violations of the kinematics of motion ($\Delta\lambda_\Sigma$) from dynamic loads, physical and mechanical properties of the hardened inner surface of the cylinder.

To ensure the speed requirement (v>0.1 m/s) for the landing of the locking element, a composite ball structure has been developed, consisting of a steel ball inside and a composite rubber shell outside, to create an elastic effect of closing the valve. A ceramic material based on zirconium dioxide (ZrO_2) was selected as a filler for the rubber compound.

The effectiveness of the use of a composite material (Steel 20 GOST 2590-88 and composite rubber compound 7B-14MA TC 38-105-1082-86 with a metal-ceramic filler), which ensures the distribution of contact stresses over the area of impact of the locking element in the area of the "conditional meridian" on the seat surface, is substantiated.

The design and manufacturing technology of the ball of the valve pair of the plunger pump from a combined material with optimal damping properties has been developed to create an elastic effect of closing the valve and evenly redistributing the cyclically varying shock load over the contact surface.

According to the results of the experiment, the following polynomial dependences were established: change in hardness from the distance to the focal plane: $HRC=-0.0119x_8^2+1.6283x_8+2.8517$; change in microhardness along the thickness of the sprayed layer at different deposition rates: $HV=-977.58h^2+2499.70h+3689.50$ at v=15 m/s; change in adhesion strength the coatings depend on the voltage characteristics of the modes and the spraying distance: $\sigma_{cl}=-1E-05l_d^3+0,0017l_d^2+0.3040l_d-17.6380$. The maximum value of the adhesion strength of the coating is achieved at a spray distance of l_d = 10 mm and a voltage of U = 170 V.

The developed laser technology for manufacturing and hardening the inner surface of the contact pair "plunger-cylinder" of small diameter (44 mm) mining pumps allows to obtain high quality (σ, porosity<7%, K_i) of the hardening surface having optimal values of coating thickness (h), surface microhardness (Hμ), surface layer hardness (61÷65 HRC), complete fusion of powder material, effective fusion of base metal particles with the sprayed surface, to reduce the thermal effect on the base metal and reduce the level of residual deformations and stresses in the pump cylinder.

To achieve optimal values of the microhardness of the pump surface (670 HV), the optimal transition zone of the material deposition of 0.8-1.45 mm was found. High microhardness is achieved at an optimal distance of 10-15 mm and a surfacing speed of 15 mm/s. A further increase in the transition zone to 1.45 mm does not significantly change the microhardness, and with an increase in thickness to 1.6 mm, the microhardness decreases sharply.

To increase the operational parameters (Hμ, Ra, σ_{cl}) of the hardened surface, the optimal characteristics of a highly concentrated laser energy source and optimal hardening modes of the inner surface of the cylinder are justified: radiation power 2000...3000 W; sputtering rate 10÷15 mm/s; diameter of the radiation focusing spot 1.5...2.5 mm; diameter of the processing laser spot – 5÷10 mm; the energy density of the laser beam is $3\cdot10^5$ W/cm^2; the distance from the focal plane is 15 mm; the mass consumption of the surfacing powder is 0.25 g/s.

The developed design of a controlled laser spraying unit allows the coating of multicomponent powder materials to be applied to the inner surface of a long cylinder (up to 6 m) with a small diameter (44 mm) of a downhole rod deep pump, ensuring a continuous and uniform laser spraying process.

A method for increasing the reliability of rod depth pump by filtering oil from mechanical impurities is substantiated. This design allows you to reduce clogging of

the filter and pump, as well as to obtain the effect of self-cleaning of the filter due to the gravitational effect of lifting and lowering the oil.

Works published on the topic of the dissertation:

1. Savinkin V.V., Ratushnaya T.Yu., Ivanischev A.A., Surleva A.R., Ivanova O.V., Kolisnichenko S.N. Study on the Optimal Phase Structure of Recovered Steam Turbine Blades Using Different Technological Spray Modes for Deposition of Al_2O_3. The 5th International Conference on Green Design and Manufacture 2019 IConGDM 2019 – Bandung, Indonesia 29-30 April 2019. – Abstract Book and Conference Program Guide, P. 64, (percentile by CiteScore Scopus 41,405) https://doi.org/10.1063/1.5118030

2. Savinkin V.V., Kolisnichenko S.N., Sandu A.V., Ivanova O.V., Petrica Vizureanu, Zhumekenova Z.Zh. Investigation of the strength parameters of drilling pumps during the formation of contact stresses in gears / Applied Sciences (Switzerland), 2021, 11(15), 7076. Quartile of the Journal (Q2, JCR) according to the SCOPUS database (SJR), percentile of the Scopus Unitescore – 63 (Materials Science/General Materials Science category) https: //doi.org/10.3390/app11157076

3. Savinkin V.V., Zhumekenova Z.Zh., Sandu A.V., Petrica Vizureanu, Savinkin S.V., Kolisnichenko S.N., Ivanova O.V. Study of wear and redistribution dynamic forces of wheel pairs restored by a wear-resistant coating 15CR17NI12V3F / Coatings 2021, 11(12), 1441. Quartile of the journal (Q2, JCR) according to the SCOPUS database (SJR), the percentile of the Scopus Unitescore – 64 (Surfaces, Coatings and Films category) https://doi.org/10.3390/coatings11121441

4. Ratushnaya T.Yu., Savinkin V.V., Ivanova O.V., Shakirova M.A. Three-way vortex mixer. Utility Model Patent No. 6809 Republic of Kazakhstan, No. 2021/1113.2 applications. 08.12.2021; publ. 14.01.2022, byul. No. 2

5. Ivanova O.V. Analysis of prospects for the development of pipeline transportation of petroleum products / Collection of materials of the VI-th ISPC of students, postgraduates and young scientists "Fundamental and applied research of young scientists". SibARA, Omsk, Russia. 02/10/2022, pp. 9-11, eLibrary ID: 48820195, RCIN https://elibrary.ru/item.asp?id=48820195

6. Ivanova O.V. Analysis of ways to increase the efficiency of low-flow wells / Collection of materials of the VI-th ISPC of students, postgraduates and young scientists "Fundamental and applied research of young scientists", SibARA, Omsk, RF. 02/10/2022, pp. 61-64, eLibrary ID: 48820207, RCIN https://elibrary.ru/item.asp?id=48820207

7. Savinkin V.V., Ivanova O.V., Macepuro E.A., Kolesnichenko S.N., Sen D.O. Downhole self-cleaning filter of centrifugal action. Utility Model Patent No. 6888 Republic of Kazakhstan, No. 2022/0010.2 applications. 11.01.2022; publ. 02/25/2022, byul. No. 8

8. Ivanova O.V., Ratushnaya T.Yu., Ivanov E.A. Analysis of modern technologies for increasing the durability of the valve assembly of an oil-producing rod deep pump / Collection of materials of the International scientific and practical conference "Trends in the development of natural and technical sciences in the modern world", dedicated to the 85th anniversary of the North Kazakhstan University named after M. Kozybaev, 11/18/2022. – pp. 572-579

9. Ratushnaya T.Yu., Savinkin V.V., Shakirova M.A., Ivanova O.V. Study of the Gas-Dynamic Features of the Design of the Gas-Air Path of the Plasmatron / Republican scientific journal "Proceedings of the University" No. 1(90), 2023, A.Saginov KTU. – pp. 42-47 https://is.ku.edu.kz/publishings/%7B6670B6EE-EAA0-4D4F-B0F5-7E24DFD677B7%7D.pdf

10. Ivanova O.V., Savinkin V.V., Sandu A.V. The study of structural materials 95Х18ІІІ in conjunction with a rubber mixture of group VI and polyurethane grade ПУСКУ-ПФЛ-100 with damping properties / International Conference on Innovative Research «EUROINVENT ICIR 2023», Iasi, 11th-12th of May 2023. – p. 98 http://www.euroinvent.org/cat/ICIR_2023.pdf

11. Savinkin V.V., Ivanova O.V., Zhumekenova Z.Zh., Sandu A.V. and Vizureanu P. Effect of New Design of the Laser Installation and Spraying Method on the Physical and Mechanical Properties the Inner Surface a Small Diameter Coated with 15Crl7Nil2V3F35ZrO_2. / Coatings 2023, 13, 514. Импакт-фактор 3,236; quartile of the magazine (Q2, JCR) according to the SCOPUS (SJR) database, the CiteScore Scopus percentile is 64 (category Materials Science/Surfaces, Coatings and Films) https://doi.org/10.3390/coatings13030514

12. Savinkin V.V., Ivanova O.V., Sandu A.V., Kolisnichenko S.N. Ensuring the Durability of Oil-Producing Pumps Through the Use of Laser Spraying Technology. Monograph/ V.V. Savinkin, O.V. Ivanova, A. Sandu, S.N. Kolisnichenko. – Materials Research Forum LLC, USA, Volume 144 (2023). – 121 c. https://www.mrforum.com/product/ensuring-the-durability-of-oil-producing-pumps/

13. Savinkin V.V., Ivanova O.V., Zhumekenova Z.Zh. Research of Modern Technologies for the Restoration of Structural Elements of Mining Pumps: Advantages and Disadvantages, Promising Technologies / European Journal of Materials Science and Engineering, Vol. 8, Issue 1, 2023: 22-29 DOI: 10.36868/cjmsc.2023.08.01.022 https://ejmse.ro/articles/08_01_03_EJMSE-22-186.pdf