Problems and criteria of quality improvement in end face mechanical seal rings through technological methods

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Abstract. In this paper are presented the recommendations for material’s selections of the mechanical seals rings and basic productive and operating requirements. The system of a directional selection of technology that ensures the required quality of working surfaces of the mechanical seals rings covers their entire life cycle. The mathematical frictional model is proposed as an instrument for calculating a linear and weighing abrasion of the mechanical seals rings and helps to improve selection’s criteria and the most rational method of strengthening.

1. Introduction
The creation of reliable seal assemblies, that ensure tightness for a long time in a wide range of temperatures and pressures, is one of the major problems in the design of pump and compressor machines and units.

One of the most common sealing elements used in pumps, compressors and various chemical apparatus (reactors, mixers, etc.) is a mechanical seal (MS). It is a sealing device consisting of two parts in the form of rings: one of which rotates with the shaft and the other is fixedly connected to the body (Figure 1).

![Figure 1. Rings of friction pairs of mechanical seals.](image-url)
Seal performance is influenced by design, technological and operational factors. The most important ones are the properties of working environment, modes of operation, material properties of a sealed connection, limits on the leakage, the resource, the total period of use, toxicity and chemical environments.

Seal rings are a friction pair, which serves as the main sealing element. Hence they are made of special materials, whose selection depends on the operating conditions. The properly selected material of the rings provides reliable, safe and trouble-free operation of the seal assembly and, therefore, the entire unit.

2. Analysis of the main achievements and publications

According to [1], the design choice is largely determined by the physical and chemical properties of the medium, its state of aggregation (gas, liquid), pressure, temperature, viscosity, content of suspended solid particles and salts, chemical aggressiveness, flammability (being heated in contact with the atmosphere), the degree of hazard to humans and the environment.

It should be noted that the correct choice of material and its mechanical and physical characteristics plays the significant role in selecting design of the sealing rings. It is the combination of the materials for friction pairs what is more crucial rather than materials per se.

In the selection of the optimal sliding couples it has to be considered the corrosion resistance and durability of the materials, the possibility of heat removal from the zone of friction and materials compatibility i.e. the ability to work without setting and jams [2].

For each case the choice of the most suitable materials of rings can be made only by a careful comparison of their working conditions, raw material properties, the changes, which occur on the friction surfaces, etc.

Some rules are proposed in [3] for the combination of materials. For example, it is recommended to combine a solid material with a solid material (a combination of the nitrided, chrome and hardened steels). Such friction pairs have a high wear resistance due to the small mutual penetration of their surfaces. The application of the running-in coating improves the reliability of pairs in the most dangerous period of work - during running-in. The application of these pairs is limited by sliding velocities. High precision manufacturing and assembly, considerable structural rigidity, rigorous running-in, improved lubrication conditions greatly expand the scope of the friction pairs made of hard materials.

In [4] a parameter is used to describe the intensity of working conditions of mechanical seals, which is the product of the pressure \(p\) in the fluid average circumferential velocity slip \(v\) in a friction pair. Depending on the parameters \(p\) and \(v\) seals are subdivided into four categories (Table 1).

| Seal category | \(P\), MPa | \(v\), m/sec | \(p\cdot v\), MPa·m/sec | Parameter definition |
|---------------|------------|--------------|-------------------------|----------------------|
| I             | \(\leq 0,1\) | \(\leq 10\)  | \(\leq 1\)              | Low                  |
| II            | \(\leq 1,0\) | \(\leq 10\)  | \(\leq 5\)              | Average              |
| III           | \(\leq 5,0\) | \(\leq 20\)  | \(\leq 50\)             | High                 |
| IV            | \(>5,0\)     | \(>20\)      | \(>50\)                 | Highest              |

In [5] it is summarizes the results of studies [6-9] and presented requirements on the materials of friction pairs, which are designed to work as the mechanical seals in contact with aggressive media:
- Resistance to aggressive environments;
- Impermeability to fluids in contact with the rings;
- Resistance to temperature gradient;
- Absence of setting and seizure;
- Sufficient frictional heat resistance;
- The maximum possible service life;
- Time stability of the coefficient of friction and its minimum value.
Depending on the operating conditions, the following materials are proposed: plastic antifriction carbon-based materials, metals (iron, steel alloys, non-ferrous metals), and other hard alloys. [1-9].

According to [10], the seals for rotors have to meet two main requirements: have the desired tightness and high reliability at a given pressure drop, rotating speeds, temperatures and physical properties of the sealed medium.

It should be noted that the mechanical seal shaft requires a minimum leakage for the operation. As a result, the gap between the rings must be very small, lubricating film has to be very thin and the surface of sealing materials must withstand the friction against each other, often at high speeds and loads. Therefore, the materials of mechanical seal surfaces must have a low coefficient of friction, sufficient hardness, good corrosion resistance and high thermal conductivity.

Mechanical seals of non-contact type (Figure 2) are widely applied in the high-speed pumps and compressors for high pressure, where the end faces of the rings are in contact for a very short time in moments of starting and stopping the machine. Guaranteed clearance size 0.003-0.004 mm between the ends of a pair leads to the fact that the sealing surfaces of the rings almost do not wear out. Despite that, their sealing rings are made entirely of wear-resistant materials such as tungsten carbide, silicon carbide, various kinds of graphites. The cost of such rings is hundreds and thousands US dollars, resulting in the high cost of seal assemblies in general.

The seal (Figure 2) comprises an axially movable ring 1, set in the housing 2, which is preloaded with spring 3 and the metal supporting ring 4, fixed to shaft 5. At the end of the working surface 6 of the ring 1 there is a set of chambers 7 intermittently arranged along the circumference of the ring. On the ring 4 there are several tangential channels 8, with middle portions of which located on the axis at the same distance as the cameras 7. The number of channels 8 is less than the number of cameras 7, so that they can communicate with the cavity of hardening medium only a part of cameras. Secondary seal 9 of the axially movable ring 1, which is shaped in the form of a thin metal shell, is made as one piece with the ring 1. This shell is shaped in a conical whisker, thickening towards the connection to the axially movable ring 1. This conical whisker has a sealing surface 10 in place of the contact with the sealing surface of the bushing 11.

Note that when the whisker (the secondary seal) contacts with the sleeve, fretting process occurs, i.e. whisker surface 10 reciprocating (with an amplitude of 3 - 4 mm) on the surface of the sleeve 11. As a result of the fretting corrosion the destruction of the contact surfaces happens. Thus, the contact surface whiskers except watertight connections should have high wear resistance.

Figure 2. A mechanical seals of non-contact type.
At the same time, the improvement of the technique demands a high and ultrahigh pressures, temperature extremes (from highest to cryogenic), corrosive environments and the like. The impact of such conditions on the tightness of detachable joints is very huge. Therefore, the use of metal composite materials, such as "basis-coating" that combine the protective properties of the coating with the mechanical strength of its foundations [11], becomes advantageous to the manufacture of mechanical seals rings.

In [12] it is analyzed the work of the gate pulse compression. It is noted that the use of such seals can save energy and resources and increase the environmental safety of the pumping and compression equipment.

The change in protective and tribological properties of the surfaces of the parts can be achieved through the formation of a special relief surfaces of friction pairs [13,14].

As a reserve of the improvement of the quality specifications can be the use of composite materials in the plated steel parts. The usage of the cladding parts with special material properties allows to create units with the necessary strength, reliability and durability [15].

Given that not all materials can be used for surfaces of mechanical seals, their choice is, therefore, crucial.

In the literature, there are no comprehensive studies aimed at developing the technology of the selection of the material for rings and their elements, the use of which will provide the maximum life of the specification. None of the available literature recommendations on the choice of materials for mechanical seals is universal.

The aim of this work is to develop the system and criterions of a directional selection of the technology that ensures the required quality of working surfaces of the mechanical seal rings by the analysis and synthesis of existing counterparts, industry experience and suggestions in domestic and foreign literature.

3. Statement of the basic material research
The system of a directional selection of technology that ensures the required quality of working surfaces of the mechanical seals rings covers their entire life cycle (Figure 3), which includes the material of rings and their elements, the technology of manufacture, maintenance etc. They are viewed through special directed choice techniques. It is necessary to consider the mutual impact of selected methods, which will ultimately affects the quality of the whole product.

Figure 3. Using of directional choosing of technology of forming surface layers of the mechanical seal ring ends at different lifecycle stages.
The need for a systemic approach to research requires analysis of the expedient use of directional selection technology to ensure the required quality of the surface layers of the rings at all stages of their life cycle. It is now obvious that the problems of improving the wear resistance of details of friction units should be carried out in close co-operation design, technological and tribological solutions. Proper selection of materials is only possible if the analysis of structural and tribological characteristics of friction unit and the conditions of its operation is carried out.

At the stage of pre-production design the design of the mechanical seal rings, which perform certain functions, is important to know the techniques, the use of which may provide the required characteristics of the surface and in accordance with the quality parameters to assign it (technological rationality of design). Production experience shows that the range of such methods can be wide.

At the pre-production technological stages the knowledge of the methods to improve the quality of the surface layers of machine parts allows to plan a rational technology of obtaining the desired properties.

As a result of research, it is possible to choose the most efficient method of producing ring billets of the required quality. Perhaps they will be made of cheaper materials, with less allowance for processing etc. It is possible a more rational use of thermal machining, reducing the number and duration of the individual stages.

Knowing the requirements that apply to the surfaces of the rings, it is possible to select those methods of machining that will be most suitable and economically feasible.

It is also necessary to know the obtained results of studies when planning and implementing the assembly process. The choice of assembly operations: welding, assembly, thermo-assembly etc. is dependent on the quality of the surface of the previous layer. This leads to a deeper analysis of the assembly process, as in the final stages of the production process the necessary characteristics of the product are finally formed.

During the formation of the surface layer with the desired characteristics control methods and testing of the seal are applied. Knowing the material and surface quality rings, it can be predicted the conditions under which mechanical seals will work better or worse and in this regard, using the obtained results, it is possible to manage the process of rational exploitation.

![Figure 4. Methods to achieve the required quality of mechanical seals rings surfaces.](image-url)
Using the directional choice of technology to ensure the required quality specifications for rings at the stage of repair allows to solve the problem to restore their state more efficiently. Practice shows that at this stage the use of research results has a significant economic impact.

The results also can be used for the rational utilization of the rings, since processing thereof largely depends not only on the material composition and structure, but also on their sealed environment (acid, venoms, foods, etc.).

Figure 4 shows a set of methods to achieve the desired quality of the contacting surfaces of the rings 1 and 4 specifications and the sealing surface of the whisker (Figure 2). This set is the practical field application of the results of academic research undertaken.

While solving the problem of improving the quality of ring surface layer, it is important to consider not only the cost but also the environmental characteristics of the process (Figure 5).

The costs of maintaining the environmental characteristics of rings are added to the overall costs. It is worth to be noted that environmental characteristics may be used as an independent optimization criteria in choosing pre-selected cost-effective options. A set of methods of forming the surface of a required quality, a number of layers in coating and equipment modes of operation can vary during optimization.

There are a lot of criterions for measuring parameters of quality of surface layers such as: full workload, the fatigue cycles limit, surface hardness, creep limit, constructional parameters of details etc. Different varieties of them can be used depend on the operating condition.

During the exploitation period, energy transformation from outside energy to energy of inside processes is occurred by temperature and diffusion mechanism. As a result, structural properties of materials could be reversed and lifecycle of whole machine will be reduced.
The main benefit of using the energy as the base criteria in technological process is the creature of mathematical model which includes all operating, technological and constructional parameters and helps to provide required characteristics of details.

Intensive mechanical loads, which are the result of outside friction processes, lead up to sharp change in mechanical and physical characteristics of detail’s working surfaces therefor the main criteria of abrasion is the energy of activation [16].

The disconnection of links is a discrete stage of activation whereby the energy of activation $A_{E}$ is a difference between the link’s energy $U_0$ and the energy of deformation $\gamma \cdot \sigma$.

Figure 6. The stages of abrasion:
1 – cold burnishing;
2 – stable abrasion;
3 – destructive abrasion.

Figure 6 shows that in the first and second stages there is the exponentially increasing reliance between work lost in friction ($A_{fr}$) and weight loss by abrasion ($\Delta m$).

It can be concluded from the experimental reliance between $\Delta m$ and $(-A_{fr})^{-1}$ that there is the proportional correlation between $\ln \Delta m$, $(-A_{fr})^{-1}$ and $E_{A}$. So the intensive of abrasion depend on a value of work lost in friction which is as much as the energy of activation $\ln \Delta m \approx (-A_{fr})^{-1}, E_{A}$.

$$\Delta m = C \cdot \exp \left( \frac{-E_{A}}{A_{fr}} \right)$$  \hspace{0.5cm} (1)

$C = \Delta m_{max}$ – value of maximal tolerable abrasive. Than,

$$\Delta m = \Delta m_{u} \cdot e^{-\frac{E_{A}}{A_{fr}}}$$  \hspace{0.5cm} (2)

The correlation (2) is the equation of abrasion.

If we assume that $E_{A} = A_{fr}$ than (2) can be transformed in (3).

$$\frac{\Delta m}{\Delta m_{max}} = e^{-1}$$  \hspace{0.5cm} (3)

Consequently, the energy of activation $E_{A}$ is the physical quantity which shows what work lost in friction is needed to serve the condition (3). $E_{A} [J]$ is a constant of abrasion.

In order to measure linear abrasion (the alteration of a detail’s dimensions) the equation (2) has to be transformed in (4)

$$\Delta h \cdot S \cdot r = \Delta h_{u} \cdot S \cdot r_{max} \cdot \exp \left( \frac{-E_{A}}{A_{fr}} \right)$$  \hspace{0.5cm} (4)
\( S \) – the area of wearing surface;  
\( r \) – density of surface layer (in the first and second stages Figure 6);  
\( r_{max} \) – density of surface layer (in the beginning of the third stage Figure 6).  
\( \Delta h_{max} \) - value of maximal depth of abrasive.  

After transformation:

\[
\Delta h = \Delta h_{max} \cdot \frac{r_{max}}{r} \cdot \exp \left( -\frac{E_A}{A_f} \right) \tag{5}
\]

If we assume that \( E_A = A_f \) then (5) can be transformed in (6) and (7).

\[
\Delta h = \Delta h_{max} \frac{r_{max}}{r} \cdot e^{-1} \tag{6}
\]

\[
\frac{\Delta h \cdot r}{\Delta h_{max} \cdot r_{max}} = e^{-1} \tag{7}
\]

Consequently, the energy of activation \( E_A \) is the physical quantity which shows what work lost in friction is needed to serve the condition (7) if densities \( r \) and \( r_{max} \) are equal.

In order to measure a value of work lost in friction for weight loss by abrasion or for linear abrasion the equation (2) and (5) have to be transformed in (8) and (9) accordingly.

\[
A_s = \frac{E}{\ln \frac{\Delta m_{max}}{\Delta m}} \tag{8}
\]

\[
A_f' = \frac{E}{\ln \frac{\Delta h_{max} \cdot r_{max}}{\Delta h \cdot r}} \tag{9}
\]

Using this mathematical system to ensure the required quality specifications for rings at the operation stage allows to solve the direct task (quantification of weight and linear abrasion when the work lost in friction is known) and the indirect task (quantification of work lost in friction when weight or linear abrasion is known). In addition, if duration of abrasion is known the rational exploitation of machine will be possible.

The results also can be used for reliable prediction of surface abrasion for wide variety of technological methods. The main criterions for system of directional choosing of technology of forming surface layers are the constants of the equation of abrasion \( (E_A, \Delta h_{max}, \Delta m) \). If the basic input dates (value of abrasion, time and operating costs) are known it will be easy to choose the optimal technology which allows to achieve pre-set surface properties (Figure 7).
4. Conclusions
This research allows to develop a common point of improving the quality of the surface layers of the mechanical seal ring ends, according to operating requirements.

It is proposed a system of directional choosing of technology of forming surface layers of the mechanical seal ring ends, which takes into account all stages of their lifecycle. Economic and environmental requirements are taken into account at the same time.
In order to achieve the required quality of rings surface, depending on its type and requirements to it, either separate methods or their combinations may be used.

It is proposed a mathematical model of abrasion which can measure the quantification of weight and linear abrasion when the work lost in friction is known for different quality of the surface layers of the mechanical seal ring.

It is developed the methodology for computing abrasion’s constants $E_A$ and constants $(\Delta h_{\text{max}}, \Delta m)$ of equation of abrasion for various materials of sliding couples.

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