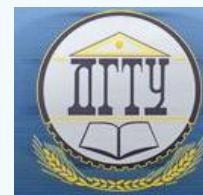# МАШИНОСТРОЕНИЕ И МАШИНОВЕДЕНИЕ
MACHINE BUILDING AND MACHINE SCIENCE

On ensuring joint tightness on the basis of technological induction[*]

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К вопросу обеспечения герметичности соединений на основе технологического индуцирования[***]

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Introduction. Some theoretical and engineering aspects of sealing joints through magnetostriction, as well as the polarization of the sealed medium under the external induction are considered. Control of surface roughness of joined parts to increase the joint density when induced by an external magnetic field is studied. The creation of electromagnetic barriers for the migration of molecules of the sealed medium through a sealer is considered. The work objective is to validate the technological conditions for sealing movable joints in the cases described above.

Materials and Methods. The conditions for ensuring the joint density are shown as a result of the contact problem solution and as a factor determined by the molecular-mechanical friction theory. Geometric, operational and tribological conditions of joint tightness are accepted. Damping properties of the fixed friction contact are determined by the molecular component. The theoretical and calculated analysis of the factors affecting the joint density is presented. Decrease in the smoothing depth, reduction of the ratio of transverse and longitudinal roughness steps, and increase in the contact area are indicated as the target results of the process preparation of the surfaces of the joint parts. Loss of tightness is defined as a specific transfer of molecules. They are transferred to the area of the joined surfaces or migrate freely through the sealer at the stages of sorption, diffusion and desorption. The predominance of any stage occurs when the entropy changes, and it is due to temperature and pressure. The schemes of sealing joints in the controlled magnetic field and of the dependence of magnetostriction and magnetostrictive stresses on the magnetic field strength are visualized.

Research Results. The stability of sealers in highly volatile and gaseous media during their polarization and magnetization in an external field is experimentally investigated. In the former case, the magnetic induction vector was first oriented perpendicular to the longitudinal axis of the joint. A drop in the magnitude of the magnetic flux was observed when the

Введение. Статья посвящена некоторым теоретическим и технологическим аспектам обеспечения герметичности соединений на основе магнитострикции, а также поляризации герметизируемой среды в состоянии внешнего индуцирования. Исследовано управление шероховатостью поверхностей стыкуемых деталей для повышения плотности стыка при их индуцировании внешним магнитным полем. Рассмотрено создание электромагнитных барьеров для перемещения молекул герметизируемой среды через герметизатор. Цель работы — обоснование технологических условий обеспечения герметичности подвижных соединений в описанных выше случаях.

Материалы и методы. Условия обеспечения плотности стыка показаны как результат решения контактной задачи и как фактор, определяемый положениями молекулярно-механической теории трения. Приняты геометрические, эксплуатационные и трибологические условия герметичности соединений. Демпфирующие свойства неподвижного фрикционного контакта определены молекулярной составляющей. Представлено теоретическое и расчетное обоснование факторов, влияющих на плотность стыка. В качестве целевых результатов технологической подготовки поверхностей деталей соединения указаны уменьшение глубины сглаживания, уменьшение отношения шагов поперечной и продольной шероховатости и увеличение площади контакта. Потеря герметичности определена как специфический трансфер молекул. Они переносятся в зону стыкуемых поверхностей или свободно перемещаются через герметизатор на стадиях сорбционного поглощения, диффузии и десорбции. Преобладание какой-либо стадии происходит при изменении энтропии и обусловлено температурой и давлением. Визуализированы схемы герметизации соединений в управляемом магнитном поле, зависимости магнитострикции и магнитострикционных напряжений от напряженности магнитного поля.

Результаты исследования. Экспериментально исследована устойчивость герметизаторов в легколетучих и газовых средах при их поляризации и намагничивании во внешнем поле. В первом случае сначала вектор магнитной индукции ориентировался перпендикулярно продольной оси

compound was under the on-load operation for 268 hours. The total operating time of the joint was 1070 hours. If the magnetic induction vector was oriented longitudinally to the shaft axis, the operating time to the correction of the field strength was 87 hours. In the gas environment, the operating time of the connection to the adjustment of the tension was 187 hours with a total operating time of 935 hours.

Discussion and Conclusions. The penetrating ability of pressurized media decreases in the "gas – vapor – liquid" series. It depends on the temperature at the joint contact. Depressurization can be traced through changes in the magnetic flux determined by the intrinsic magnetic permeability of the molecules of the sealed medium as they penetrate the interface surface.

To increase tightness, it is required to suppress the activity of molecules. For this purpose, ionization and induction in the constant and alternating magnetic field with the intensity of <60 kA/m are used.

соединения. Установлено падение величины магнитного потока при работе соединения под нагрузкой в течение 268 часов. Общая наработка соединения составила 1070 часов. Если же вектор магнитной индукции ориентировался продольно оси вала, наработка до момента коррекции величины напряженности поля составила 87 часов. В газовой среде продолжительность работы соединения до момента корректировки напряженности составила 187 часов при общей наработке 935 часов.

Обсуждение и заключения. Проникающая способность герметизируемых сред уменьшается в ряду «газ — пар — жидкость». Она зависит от температуры на контакте соединения. Разгерметизацию можно отследить по изменениям магнитного потока, определяемого собственной магнитной проницаемостью молекул герметизируемой среды при их проникновении на поверхность стыка. Чтобы повысить герметичность, необходимо подавить активность молекул. Для этого применяются ионизация и индуцирование в постоянном и переменном магнитном поле напряженностью <60 кА/м.

Introduction. The theoretical basis of hermetology is presented in the works of G.A. Golubev, A.V. Chichinadze, V.P. Tikhomirov, L.A. Kondakova, G.V. Makarova, H.H. Wachter, E.Mayer, R.H.Waring, etc. It is known that tightness is mostly due to two factors:

- stability of the processing density of abutting rough surfaces of the sealer parts;

- stability of the sealer material properties and the sealed medium excluding the penetration and migration of molecules through its sealer beyond the interface.

The conditions for ensuring the joint consistency are justified through solving the contact problem and are largely determined by the principles of the molecular-mechanical friction theory [1, 2, 3]. The mentioned approach remains one of the fundamental in hermiticity engineering.

Penetration of sealed media (liquids, gases) through the sealer is described by the physical model of S. Slichter, I. Kozeni, T. Carman and D.K. Kollerov (for porous polymers). From its analysis, it follows that the volume flow of the medium through the seal is determined by the length of the free path of the molecules [4, 5, 6] and depends on the following:

- microroughness height of solid surface - R_{max},
- joint density - P,
- relative approximation - ε,
- geometrical dimensions of seal.

Specifically, the fretting operation is initiated by boundary structures which are different polymer seals, liquids and films on the interfaces at the amplitudes of contact vibrations less than 0.05 mm. These media can act as catalysts; that causes a decrease in the technologically secured design value of the specific pressure on the seal and increases leakage.

The amplitude and frequency of the relative displacements of the joint parts can be reduced through controlling the joint density, for example, through increasing the nominal pressure on the seal. The studies performed on polymers in the friction units [7] show that the joint density and contact rigidity depend largely on the compressive force of surfaces and on their intermolecular activation:

$$F_{mp} = aS + bP_y,$$

where F_{mp} is friction force; a is average intensity of the molecular component of the friction force; S is true contact area; b is coefficient of the mechanical component of the friction force; P_y is surface compression force.

Consequently, the molecular component aS is proportional to:

- the true contact area,

- the intensity of mutual adhesion of contacted materials.

Both of these indicators can be increased through plastic saturation along the interface plane, as well as during the alignment of the joint parts. Similar conditions can be created on the basis of magnetostrictive effects, which are pronounced to a greater degree for textured materials. Such conditions are applicable also in cases when reloading of joint parts is hindered or not provided for by the engineering performance standards.

A decrease in the penetrating power of sealed media is predicted when a mobile spherulitic structure of the sealer is formed or modified by sealing with low-modulus materials [8]. However, the conditions that develop at drastically negative temperatures and under cracking of the polymer sealer require special consideration. In these cases, differences in the temperature linear expansion coefficients with metals are observed; therefore, to control the permeability of the sealed medium molecules through creating electromagnetic barriers for them is of interest.

Now then, this work objective is to study the technological conditions for ensuring the joint tightness based on the induction effects created in the materials of the joint parts and in a sealed environment.

Materials and Methods. The conditions for joint tightness follow from the conclusions of the Lame problem, in which the boundary factors are:

- geometric (for example, l - length of the contact of surfaces and d - diameter of the mating parts);

- operational (R_{oc} - longitudinal axial force or $M_{кр}$ - torque tending to move one part relative to another);

- tribological (f - friction factor) determining the moment of pressing or turning.

Friction locking is provided while minimizing the amplitude of the relative displacements of the surfaces, at contact stresses not exceeding the region of the damping capacity of materials [7].

Damping properties of the fixed friction contact are determined, in particular, by the molecular component. Moreover, the interface with the textured (anisotropic) structure in the direction of ensuring high damping capacity allows for a higher value of the critical vibration loads in a wide frequency range [8].

In addition, when an external induction changes R_a roughness parameter due to the magnetostrictive effect, they can affect the joint density. This is explained by the comparability of magnetostriction values and the sizes of blocks of structural components (about $10^{-4} - 10^{-5}$ m). Moreover, the technological texturing in crystallographic directions with pronounced maxima of the elastic or plastic properties of materials causes a maximum magnetostriction effect at the unidirectional position of the magnetic induction vector. This causes an increase of the nominal pressure value in the preloaded demountable joints since part of the stresses spending on the parts' compliance is compensated by magnetostrictive stresses within the elastic properties. In permanent joints, on the contrary, part of the stresses can be spent on the plastic saturation of the contact. For the same reason, the actual preload is greater than the calculated one.

P is joint density coefficient with magnetostrictive effect:

$$P = (V_{1m(hkl)} + V_{2m(hkl)})k_{(hkl)} / V_{общ}. \tag{1}$$

Here, $V_{1м(hkl)}$ is the material volume of the rough layer with hkl texture; $V_{2м(hkl)}$ is the material volume of an incompressible seal extruded into the gaps; k is the magnetostriction coefficient; $V_{общ}$ is the total volume of the rough layer.

It is known that the presence of waves causes a decrease in the bearing contact area by a factor of 5–10 [9]. Therefore, the solution to the contact problem in the aspect of ensuring the joint tightness requires consideration of the waviness of the surfaces.

The height and step parameters of roughness are interrelated; therefore the technological preparation of the surfaces of the joint parts should be aimed at the following results:

- reducing the depth of smoothing (R_p);

- reducing the ratio of steps of transverse and longitudinal roughness;

- increasing the contact area and R_p / R_a ratio.

As a rule, there is no direct relationship between the tolerance value and the height of irregularities; however, it should be noted that the depressions on the surface profilogram turn out to be reservoirs in which by-products accumulate, which initiate surface weakening.

While ensuring the joint density due to the preload, S_N compliance of the compound is represented as:

$$S_N = x(t) + (\xi_{(hkl)}(B)k^`) / N^*, \tag{2}$$

where $x(t)$ is normal contact displacement in the function of time; $\xi_{(hkl)}(B)$ is the magnetostriction tensor at a regulated crystallographic ordering considering plastic deformations in the coating and changing with magnetic induction; $k`$ is coefficient of crystallographic ordering; N^* is dynamic load.

When the compounds operate under the hydrostatic pressure of the sealed medium (liquid or gas), loss of tightness is expressed in a certain form of transfer of molecules. They are transferred to the area of the joined surfaces or migrate freely through the sealer at the stages of sorption, diffusion and desorption. The predominance of any stage occurs when the entropy changes, and it is due to temperature and pressure.

The simplest case of phase transfer in seals is the flow of a viscous incompressible fluid in a porous medium. The determination of the leakage value follows from the Darcy law. However, in this case, it is not considered that the sealing joint, in contrast to the porous solid body, is formed as a result of the contact of two surfaces. Therefore, under the load increase and the alignment of the surfaces, individual contact spots can form isolated volumes (effective channels). Their number decreases with increasing load until the formation of a hydrodynamic film along the seal perimeter [10–11]. Thus, considering the conductive capacity of most sealed media, it is advisable to investigate tightness from the standpoint of polarization and external induction.

According to [12], when a medium passes through an electric current source or ionizer, molecules obtain q charge. If a charged particle with an initial velocity v moves in a uniform magnetic field along the magnetic induction lines B of the external field, then the angle α between the vectors of v and B is equal to zero. The magnetic field does not affect the particle (the Lorentz force is also zero), and it moves uniformly and rectilinearly.

If a charged particle moves with velocity v in a magnetic field perpendicular to vector B, then the Lorentz force $F = q[vB]$ is constant in magnitude and perpendicular to the particle trajectory, which prevents its displacement (Fig. 1, *a*).
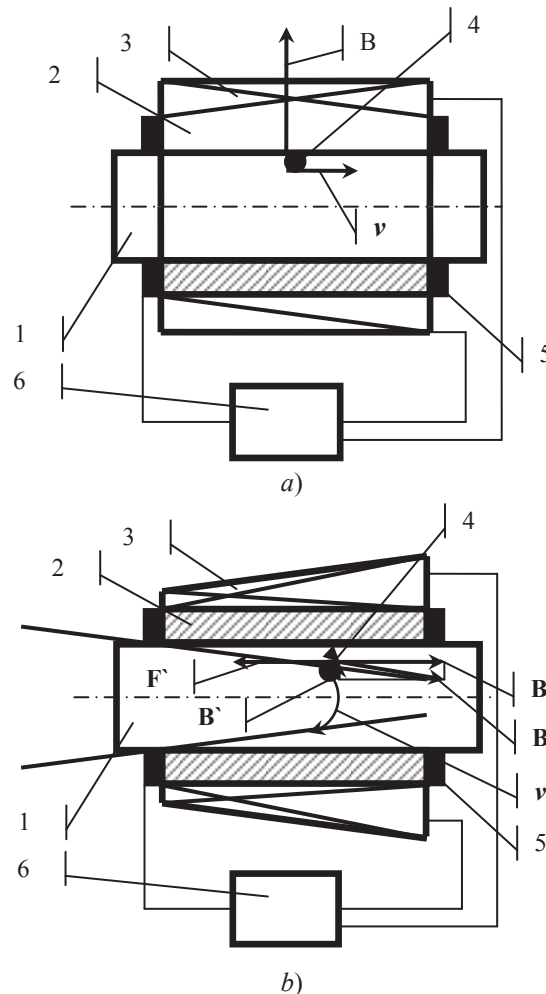

a)

b)

Fig. 1. Schemes for sealing joints in controlled magnetic field: in uniform field of toroidal inductor (*a*); in inhomogeneous field solenoid (*b*); 1 is shaft; 2 is sleeve; 3 is magnet; 4 is charged medium particle; 5 is source of electric current (or ionizer); 6 is automatic solenoid control unit with voltage generator); v is orbit of positively charged medium particle

Assuming the direction of medium motion, knowing its electric potential, viscosity, density, penetrating ability, and changing the field strength and the position of the magnetic induction vector, it is possible to provide the Lorentz force in quantities sufficient to completely suppress the motion. Thus, the effect reactive to the hydrostatic pressure is realized.

Similarly, in an inhomogeneous magnetic field, the component of magnetic induction B` creates force F ', which pushes the particle into the region of a weak field (see Fig. 1, *b*). Initially, the particle moves along the radius of constant magnitude with velocity *v*. However, its own magnetic field counteracts the externally induced one, and this explains the extreme instability of its state. As a result, the particle is pushed into the field region with a reduced voltage.

The sealing effect is based on creating – by the magnetic field – the reactive repulsion of pre-charged medium molecules penetrating the interface. Whereby, the degree of sealing depends on the magnetic inductance, the value of which is set through the strength of the current considering the relative magnetic permeability and form factor of the inductor.

It can be assumed that the conditions of joint vacuumization are created when the surfaces of the mating parts come closer to the appearance of molecular (adhesive) interaction. In this case, the magnetic permeability of the materials of the joint components is represented by the ratio of the magnetic fluxes in the material Φ and in vacuum $\Phi 0$ ($\mu = \Phi/\Phi_0$). Under the assumption of $\Phi = \Phi_0$, the magnetic permeability of vacuum can be taken as a unit ($\mu = 1$).

In the medium with constant magnetic permeability, the magnetic field induction is proportional to its density. Consequently, the magnetic flux from the external field, initially defined for vacuum, depends on the magnetic permeability of the medium. Its presence at the interface, due to its own magnetic permeability, either increases the magnetic flux (in paramagnetic media), or decreases it (in diamagnetic media).

Thus, it is possible to evaluate and correct the performance of the sealer in the induction state through changing the magnetic flux and, accordingly, magnetic induction.

Research Results. The crystallographic areas described below can be taken as regulated directions under the process part texturing.

1. For detachable joints without a polymer sealer: [110] (for structures with body-centered cubic (bcc) lattice), [111] (with face-centered cubic (fcc) lattice), [1000] (with hexagonal close-packed (hcp) lattice).

2. For permanent joints and connections with a sealer: [100] - [111] (with bcc lattice), [100] - [110] (with fcc lattice), [0001] - [2110] (with hcp lattice).

When the magnetic induction vector is established in the indicated directions, the magnetostriction λ in the crystals turns out to be field oriented. This is because its magnitude is non-linear to the field strength and is determined mainly by the position of the easiest magnetic axis [13, 14].

In the absence of preliminary texturing, a mean change in roughness for structures with cubic lattices is represented as:

$$0 \le \Delta \overline{R_a} < \left(\frac{2}{5} \lambda_{100} + \frac{3}{5} \lambda_{111} \right) d`, \qquad (3)$$

where λ_{100}, λ_{111} are magnetostriction constants along the [100] and [111] crystallographic directions; d` is an average size of the dispersed structural components.

In the case of texturing in the directions [100] or [111], when the field is oriented along the normal to the surface (Fig. 2), the changes in roughness (R_a) will be:

$$0 \le \Delta \overline{R_a} < \lambda_{100} \overline{d} / k, \qquad (4)$$

$$0 \le \Delta \overline{R_a} < \frac{3}{4} \lambda_{111} \overline{d} / k, \qquad (5)$$

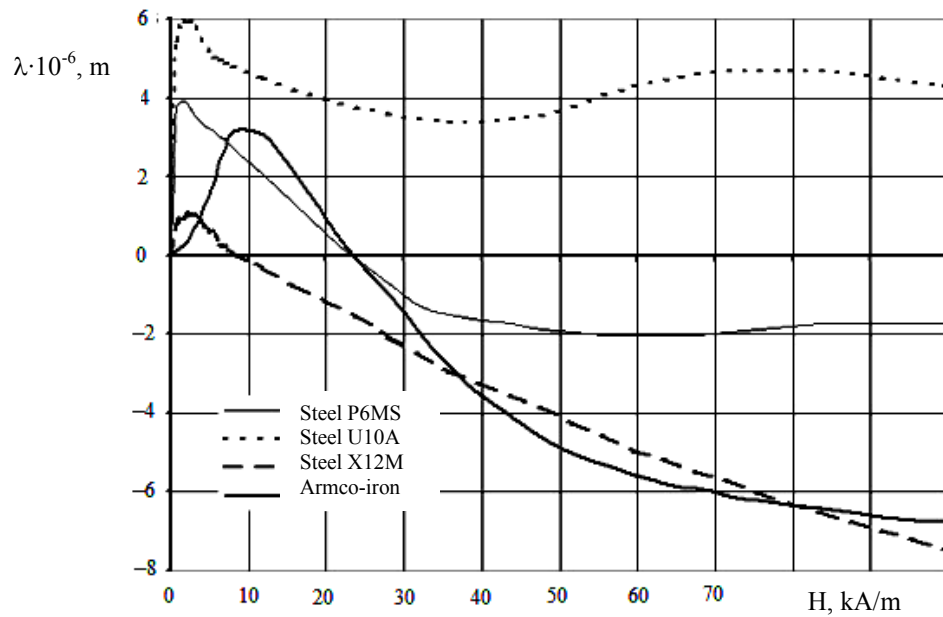where *k* is demagnetization loss factor.

Fig. 2. Magnetostriction λ – magnetic field intensity H dependence

Valves with a seat made of X12M steel with a coating in the direction [111] of $CoFe_2O_4$ cobalt ferrite coating with thickness of 20×10^{-5} m (R_{max} 2.4 μm, $r_1 = 52\times10^{-3}$ and $r_2 = 50\times10^{-3}$ m) and a brass valve by the amount of leakage flow of Q, μPa • m^3/s of helium ($T = 77$ K) are tested. It is established that, during the compound magnetization in the field of 60 kA/m, this value is 780–10240. The number of shutter cycles is 200–5000, respectively. Under similar test conditions for a saddle-valve pair in the absence of a magnetic field and prior texturing of saddles, the Q value was 960–15340 μPa • m^3/s, respectively.

With an increase in the magnetic field strength, no major changes in the connection health are established. Apparently, this is due to the fact that effective magnetostriction stresses are formed in fields <40 kA/m (Fig. 3). This conclusion is consistent with the results of the magnetostriction study.
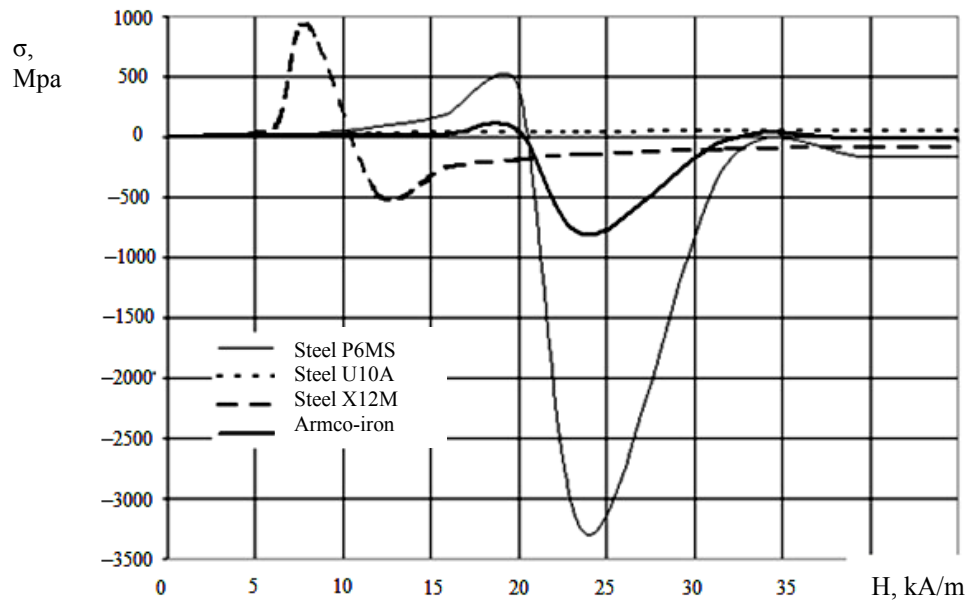

Fig. 3. Magnitude of magnetostriction stresses σ – magnetic field intensity H dependence

Changes in the properties of the sealed medium, the materials of the sealer and the temperature affect the penetrating ability and tightness in general. The permeability of media decreases in the "gas - vapor - liquid" series. With that in mind, the performance of sealers in volatile and gaseous media during their polarization and magnetization in an external field was investigated.

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At the end of a rigid detachable shaft – copper hub connection, a source of electrical current was attached, one of the poles of which was fixed to the ends of the hub. At that, the second pole had a minimum clearance with the shaft generatrix.

The joint was placed between the poles of a toroidal electromagnet connected to the automatic control unit with a voltage generator, a voltmeter and a webermeter. The magnetic induction vector was oriented perpendicular to the longitudinal axis of the joint. The joint was installed in a chamber filled with diamagnetic benzene. Pressure of 30–35 kPa was developed in it. The sleeve was rigidly fixed, after which the source of electric current and the inductor were turned on, and the magnetic field strength was set at 60 kA/m. The shaft was mechanically loaded in the radial and axial direction relative to the sleeve in a symmetrical alternating cycle with the load of 1.5 N with the frequency of 50 Hz. The tests were performed until the reduction of the magnetic flux recorded upon the webermeter indication. This moment characterized the violation of tightness expressed in the penetration of benzene to the joint surface. The inductor automatic control unit corrected the voltage in the toroid, due to what the magnetic field strength was set equal to the initially predetermined one.

A drop in the magnitude of the magnetic flow was observed when the joint was under the on-load operation for 268 hours. The total operating time of the joint was 1070 hours. The criterion for the completion of the tests was the reduction of the interval of operating time until the moment of correction of the magnitude of the magnetic force. It should exceed 60 kA/m. This is due to the need to increase the operating time to the value corresponding to the previous cycles.

With the orientation of the magnetic induction vector longwise the axis of the shaft under similar test conditions, the operating time until the correction of the field strength was 87 hours.

The simulation of the operating conditions of the joints in the gas environment was carried out in a similar way. An ionizer was mounted on the shaft which was attached to the ends of the sleeve. The joint was placed in a solenoidal inductor, the density of the turns of which increased from the end of the sleeve. As a result, a non-uniform magnetic field was generated, the intensity of which increased from the end of the solenoid.

The joint was placed in a chamber under the pressure of 30–35 kPa with paramagnetic nitrogen, after which the ionizer and inductor were switched on. The shaft was loaded in the modes described above with periodic recording of the magnetic flow. The moment of changing its initial value characterized the violation of tightness and the penetration of nitrogen to the interface. In this case, the inductor automatic control unit provided a reduction in voltage in the solenoid winding to the value corresponding to the magnetic field strength of 60 kA/m.

The operating period of the joint until the adjustment of H value of was 187 hours with a total operating time of 935 hours. The long duration of the tests caused the correction of the magnetic field strength with the time interval of less than 187 hours.

Discussion and Conclusions. Reduction of leakage through the seals is provided by the joint density (specific pressure p_a) management while reducing the amplitude and frequency of the relative displacements of the joint parts. The latter is obtained through increasing the true contact area and the intensity of mutual adhesion of the contacted materials, in particular due to magnetostriction effects. In this case, the level of magnetostriction stresses should not cause plastic deformations of the sealer (ie, $p_a \approx 1.1 \, \sigma_m$) and can be provided in the fields up to 40–50 kA/m. As the complex roughness parameter Δ changes due to magnetostriction, an increase in the contact bearing area is observed, mostly due to the material whose elastic modulus is lower and the magnetostriction is higher.

The impact of the bearing contact surface area, which increases with magnetostriction, grows with decreasing the smoothing depth R_p and the ratio of of transverse and longitudinal roughness steps. As a result, the nominal pressure in the joints grows due to the compensatory effect from the side of magnetostrictive voltages. Magnetostriction is stimulated by crystallographic magnetic anisotropy, in particular under technological texturing. In the "gas - vapor - liquid" series, the penetrating power of sealed media decreases. It is dependent on the temperature at the joint contact. Depressurization is detected through changes in the magnetic flux under the influence of the intrinsic magnetic permeability of the molecules of the sealed medium as they penetrate the interface surface. You can increase the tightness if you suppress the activity of molecules. For this purpose, ionization and induction in the constant and alternating magnetic field with the intensity of <60 kA/m are used.

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