Increasing of durability of mechanical seals of oil and gas centrifugal pumps using tungsten-free cermet with Cu-Ni-Mn binder

T A Shihab¹, L S Shlapak², N S Namer¹, P M Prysyazhnyuk², O O Ivanov², M J Burda²

¹Engineering Technical College of Baghdad, Middle Technical University, Alzafaraniya str., Baghdad, Iraq
²Institute of Mechanical Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, Ivano-Frankivsk, Karpatska St. 15, 76019, Ukraine

E-mail: pavlo1752010@gmail.com

Abstract. The rational materials selection for friction pairs is an important prerequisite in promoting of reliable operation of mechanical seals used in centrifugal pumps. The experience of mechanical seals exploitation shows that most preferable is combination of “hard” and “soft” materials. As “hard” materials ceramics based on SiC, Al₂O₃, Si₃N₄, are the most commonly employed and for “soft” materials metal alloys, composites and carbon materials are widely used. In this study chromium carbide based composite metal-ceramic material with copper-nickel-manganese binder was developed for using in mechanical seals rings friction couples with silicon carbide (SiC) ring. Metal-ceramic sealing rings were manufactured by infiltration of pre-sintered porous chromium carbide skeletons with Cu60-Ni20-Mn20 melt at 1150 °C in protective (argon) atmosphere. Results of experimental investigations and theoretical modelling of heat transfer during friction, show significant advantages of proposed materials combination over ceramic-ceramic pairs through its better tribological characteristics and resistance to thermal shock. Industrial testing allows us to conclude that using of mechanical seal rings of proposed materials combination almost completely prevents failures of sealing rings surfaces caused by thermal cracking.

1. Introduction

Mechanical seals are widely used in the oil and gas industry for sealing the centrifugal pump shafts. The reliability of the mechanical seal is one of the defining characteristics of the pump’s performance, and according to statistics, almost 70 % of repair work on the rehabilitation of centrifugal pumps is associated with failure of the sealing elements for a number of reasons as shown in figure 1. This leads to the forced stopping of technological lines and, as a result, significant economic costs. In view of this, considerable attention is paid to the materials of the sealing elements in the pumps of the leading manufacturers, so their value often reaches ~ 20 % of the pump price.

Despite the large number of constructional designs [1], the typical design of the mechanical seal shown in figure 2, it involves the presence of moving and stationary rings that seal the surface perpendicular to the surface of the shaft, the metal elements provide for fixing and clamping the rings. While rotating of the shaft the contact surfaces of rings is in the gap with width of 0.5 - 2 μm, and due
to the heat generated by friction, conditions for changing the composition of the working environment and its evaporation are created.

Figure 1. Main causes of the mechanical seals failure [1].

Thus, for the characteristic of the stress conditions of the mechanical seals, a parameter which represents the product of the pressure of the working environment $p$ on the average slip velocity $v$ is used. Depending on the value of the parameter $pv$, according to the classification proposed by the Mayer [2], mechanical seals are divided into four categories as in the following table 1:

Table 1. Classification of mechanical seals by parameter $pv$.

| Category | $p$, MPa | $v$, m/s | $pv$, MPa·m/s | Parameter |
|----------|----------|----------|---------------|-----------|
| I        | 0.1      | 10       | 1             | Low       |
| II       | 1        | 10       | 5             | Medium    |
| III      | 5        | 20       | 50            | High      |
| IV       | 5        | 20       | 50            | Highest   |

Depending on the environment that being pumped, in accordance with [3], mechanical seals are divided into four groups: seals for non-aggressive environments (water, petroleum products); 2) seals for aggressive environments (acids, alkalis, products of the petrochemical industry); 3) seals for environments with a high content of solid particles (ground water, drilling mud); 4) special sealing.

For various designs of the mechanical seals, which in particular are considered in [3], the same requirements apply, the main of which are: 1) the maximum possible sealing ability; 2) the maximum possible durability (the lowest wear of rings); 3) absence of necessity for frequent maintenance; 4) the minimum coefficient of friction and, accordingly, heat generation; 5) low cost.

In most cases, sealing rings fail due to the following reasons: a) high local temperature, which occurs on the mechanical seal faces and causes surface cracking; b) insufficient quality of friction, which leads to increasing pressure of the leaks; c) insufficient strength of the sealing materials, such as ceramics, fluorooplasts; d) cracking of metal-ceramic composites caused by thermal stresses; e) fluid leakage through the pores of the sealing material caused by increasing pressure, for example, for iron graphite, carbon graphite, and others. The wear of sealing rings in mobile joints can be divided into 5 groups: 1) adhesive; 2) abrasive, resulting from the contact interaction of the roughness of the two roughly treated surfaces; 3) corrosive, which is caused by chemical reactions, in particular high temperatures in the sealing gap; 4) superficial, caused by formation in contacting surfaces networks of cracks that arise under the influence of thermal stresses and fatigue; 5) erosion, which occurs as a
result of erosion of liquids and gases at high flow rates. During operation, there can be one type of wear or a combination of them.

In general case mechanical seals work in rather favorable friction modes from semi-liquid to liquid, but along with this are quite common cases when the seal works in the modes from boundary to dry friction. Dry-friction modes in pump shaft seals are observed, for example, at the initial start-up, in case of fluid supply failures, etc. This leads to a significant temperature difference and, consequently, the appearance of thermal stresses followed by thermal cracking of the working surfaces of the rings. Tests and operation of the mechanical seals shown that thermal cracking of rings of friction pairs is observed quite often. In some cases, after the detection of cracks, the seals continue to work with increased fluid flow and increased wear, which is accompanied by an increasing in non-flatness and a decreasing of the surface quality as it is shown in figure 3.

![Typical surface failures of the seal faces caused by thermal cracking.](image)

A key factor that determines reliability and durability of mechanical seals is the correct selection of seal face materials. The faces must combine wear- and crack resistance, high thermal conductivity together with chemical stability in given sealing environments. Sealing rings are produced of a wide range of materials including metal alloys, ceramics, cemented carbides etc., using different powder metallurgy techniques (liquid-phase and solid-state sintering, infiltration and hot isostatic pressing) as well as casting followed by thermal treatment [4]. The most commonly used metal alloys for producing of sealing rings are high chromium stainless steels [5], modified Meehanite and Ni-resist cast irons, aluminum bronze and alloys of the Co-W-Cr system (stellites) [6]. In the general case, producing of sealing rings by powder metallurgy is more preferable than by other processes because of possibility to obtain fine composite microstructure. Comparison of two stellites with the same chemical composition produced by different manufacturing processes performed in [7] shows, that contact fatigue performance of the stellite produced by powder metallurgy was approximately two orders of magnitude better than cast stellite, due to finer microstructure consisting of hard carbide inclusions in a tough matrix. Ceramic seal rings are usually manufactured of SiC and Al₂O₃-based materials due to their high wear resistance and chemical stability in many environments. SiC-based materials are produced by reaction infiltration of molten Si into porous SiC preforms enriched with carbon (reaction bonded SiC) [8] or sintering SiC at 2000-2200 °C with small additions of oxides (direct sintered SiC) [9]. The main advantages of SiC-based material in comparison with other ceramics (except for AlN) is the rather high thermal conductivity.

The most widely used cermets for the production of sealing rings since the 1960s are tungsten cemented carbides of WC-Co and WC-Ni systems with binder content ~ 6 - 15 wt. %, manufactured by liquid-phase sintering [10]. Such cermets are using as tribotechnical materials due to the high modulus of elasticity of the carbide phase, hardness and toughness during bending and compression (the highest among all known cermets), high thermal conductivity (depending on the content of the metal component). Tungsten cemented carbides can be used rationally in pairs where there are significant specific loads (III-IV group) and the presence of abrasive particles is assumed. Despite its versatility, the sealing rings of tungsten cemented carbides of the WC-Co system have a number of
disadvantages due to the low chemical resistance of cobalt, which dissolves even in chemically pure water, high material density, which complicates the operation of high-speed friction pairs, as well as high cost. As an alternative to WC-based cemented carbides the metal-matrix composites based on refractory compounds of Cr, Ti, Nb etc. [11] and its combinations are candidate materials for sealing rings manufacturing, because of their lightweight, high microhardness and chemical stability. For such composites, the age hardenable binder alloys based on Ni, Cu et al., are promising for using due to their high mechanical and tribological properties [12, 13].

2. Experimental study
Among the known powder metallurgy techniques which can be used for the producing of tribotechnical materials based on metal-ceramic systems, method of infiltration of porous ceramic skeletons with molten alloy has some important advantages, namely: possibility of manufacturing products of complex configuration; absence of shrinkage, which greatly simplifies the technology of manufacturing products; the possibility of using as a metal component of alloys, powders which are not produced serially (the metal components can be used in the form of waste, sludge, chips, etc.); the simplicity of technology, which is ensured by the absence of labor-intensive mixing and grinding operations of the original components and the use of standard furnace and press equipment; low influence of harmful impurities (first of all, oxide phases).

The choice of the carbide phase as a composite’s component for manufacturing of mechanical sealing rings was carried out taking into account the following basic characteristics: high level of hardness and elasticity, corrosion resistance and chemical stability, high thermal conductivity, good wettability by binder metal phase; low cost. Such requirements can be most fully ensured by using of refractory carbides of IV - VI group metals of the periodic system of elements. Tungsten monocarbide (WC) is the most common among these compounds due to the highest modulus of elasticity (720 GPa). However, the widespread use of tungsten cemented carbides of WC-Co and WC-Ni systems for the manufacturing of sealing rings for centrifugal pumps is in many cases not justified due to the worldwide trend of rising prices for tungsten raw materials. Besides the main world exporter of tungsten raw materials (84%) is the China, which at the same time is also its primary consumer (more than 50 % of world demand). Therefore, in order to save energy resources, the search for alternative materials for tungsten cemented carbides, in particular tribotechnical purposes, remains an urgent problem in the oil and gas industry wear parts equipment production. An alternative material for the production of mechanical seals sealing rings is the higher chromium carbide (Cr$_3$C$_2$), which is characterized by a rather high level of physical and mechanical characteristics, along with a high corrosion resistance in various chemically active gas and liquid environments. In addition, the cost of the metal component of chromium carbide is practically 10 times lower than that of tungsten carbide, and its density is lower by about 2.3 times. At the same time, the level of mechanical properties of Cr$_3$C$_2$ is relatively high along with relatively high thermal conductivity as shown in table 2.

| Compound | Microhardness, GPa | Density, g/cm$^3$ | Thermal conductivity, W/m×K | Thermal expansion, $\times10^6$ K$^{-1}$ |
|----------|--------------------|------------------|----------------------------|----------------------------------|
| Cr$_3$C$_2$ | 18 | 6,7 | 13 | 11,7 |
| WC | 17,1 | 15,7 | 29 | 3,9 |

The important difference of Cr$_3$C$_2$ from most refractory carbides of IV - VI group metals of the periodic system of elements is high wettability of copper and copper alloys [12]. In this case chromium carbides are also characterized by the ability to form solid solutions with manganese carbides, microhardness of which is higher than the initial components, and its concentration
dependences in the $Cr_3C_2-Mn$ systems are described by curves with extremum [10, 13]. This creates the preconditions for increasing the properties of cermet based on chromium carbides by their alloying with manganese from infiltration melt. Taking into account wettability of copper, values of microhardness and thermal conductivity of carbide phase of cermets for mechanical seals, comparative analysis (figure 4) shows that VC has the most successful combination of such characteristics. However, taking into account the density, the comparative analysis of the relative cost of the metal components of carbides (figure 5) shows that V cost is higher practically in 3.5 times than for Cr. Although the relative cost of Ti is lower than Cr almost twice, but the titanium carbides are poorly wetted with copper, which makes impossible the production of materials in the TiC - manganese cupronickel system.

![Figure 4. Comparative characteristics of copper wettability, microhardness (▲) and thermal conductivity (■) of some refractory carbides of IV – VI group metals of the periodic system of elements [14].](image1)

Thus, based on the comparative analysis of the properties of the carbide phases, and its economic consideration, the system: $Cr_3C_2 – Cu-Ni-Mn$ was chosen as one of the most suitable for the manufacturing of sealing rings. $Cr_3C_2$ powders of the TU 14-22-28-90 and TU 6-09-03-10-75 grade with average particle size of 6 to 120 μm and manganese cupronickel of the MNMts 60-20-20 (TU 48-21-486-75) grade were used as an initial component for production of sealing rings. Samples for research were obtained by powder metallurgy from powders prepared in the following way: (different fractions powders of $Cr_3C_2$ were mixed in a gravity drum mixer with a plasticizer (5% solution of rubber SKK-3 GOST 14925-79 in benzene BR-1 GOST 443-76) for 12 h. After drying the granulation was carried out by sieving through sieve with a cell size of 1 mm.). The obtained pellets were pressed into the preforms of the required ring form by the method of double-sided cold pressing in the steel mold. The produced porous skeletons with an open porosity of 20 - 40 % were placed in corundum crucibles with MNMts alloy weights (calculated for 100 % pore filling). After that, the heating of the preforms in the vacuum furnace was performed with isothermal holdings according to the mode shown in figure 6. At stage I, during slowly heating up to 900 °C, the removing of "light" fractions of plasticizer begins. Slow heating at this stage is necessary to preserve the original form of preforms. At stage II, isothermal holding at 900 °C was carried out to ensure forming interparticle contacts due to interdiffusion interaction and formation of morphology of capillaries in porous preforms. After that, the heating was carried out to 1100 °C (stage III) and isothermal holding at that temperature. At this stage, melting of MNMts alloy and its infiltration into presintered porous carbide skeletons occurs. Further, after cooling to 600 °C, an isothermal holding was made to homogenize the binder alloy (stage IV) and further cooling to 400 °C and isothermal holding at that temperature for $\sim 360 \cdot 10^3$ s to

![Figure 5. Relative cost of metal components of carbide phases for use as material for mechanical sealing rings.](image2)
provide a dispersion strengthening of the binder due to precipitation of intermetallics of the Mn$_x$Ni$_y$ type (stage V).

![Graph](image)

**Figure 6.** Mode of obtaining experimental samples from cermets of the Cr$_3$C$_2$–MNMTs system.

Taking into account the morphology of the porous carbide skeleton and the temperature-concentration dependences of the surface energy of the MNMTs alloy and its viscosity, the infiltration kinetics was described by the equation derived from the Darcy law using the JMatPro software. To detect the shape and size of the structural components of sealing ring material, as well as the bonding between them, scanning electron microscopy (SEM) was done using CarlZeiss EVO 40XVP electron microscope, with the energy dispersive X-ray spectroscopy (EDS) system (INCA Energy – 350). X-ray phase detection was performed on a DRON-3 diffractometer, in filtered CuKα and MoKα1 radiation. The character of the distribution of the structural components of the ring material by size was carried out using the ImageJ software by random sections method. According to the principles of stereometric metallography, the number of sections was > 100, and the number of size groups did not exceed 12. The analysis was carried out on electron microscopic images of the reflected electrons obtained in electron backscatter diffraction BSD mode, which allowed to determine the contrast between the phases depending on their density.

The tests of performance characteristics of mechanical sealing rings with the purpose of determining their stability in conditions of dry friction that correspond to the initial stages of starting the centrifugal pump with insufficient quantity of the working environment were carried out for pairs of metal-ceramics (proposed cermet) – ceramics and ceramics – ceramics. As is shown in figure 7 the metal-ceramic ring 1 was fixed in the housing 3, and the ceramic ring 4 was mounted on the intermediate sleeve, which was cut onto the shaft. The clamping of the rings provided with a set of ten springs embedded in the sleeve 5. To determine the coefficients of friction, the shaft with mounted face seal was connected to the inductive friction torque sensor, which was connected to an ADC converter. The temperature was measured using a thermocouple placed at a distance of 1 mm from the friction contact zone, which was also connected to the converter.

The friction coefficient of chosen friction couples was measured at a constant load (~ 1 MPa) as a function of sliding speed in the interval 0.2 – 5 m/s. Friction tests were performed without any working environment in order to reproduce dry friction conditions which often appears in mechanical seals during pump starting period and lead to the thermal cracking of the seal faces.
Figure 7. Stages of the mounting of mechanical seal on the test stand: a – mounting the rings into the holder; b – installation of elastic elements; c – fastening for rings in the case; d – mounting of the mechanical seal on the shaft of the tribometer (SMC-2); 1 – metal-ceramic ring; 2 – intermediate sleeve; 3 – holder; 4 – ceramic ring; 5 – elastic elements; 6 – SMC-2 shaft; 7 – assembled mechanical seal; 8 – mechanical seal is mounted on the tribometer.

3. Theoretical model

For heat transfer calculations, the structure of the material of rings was modelled by analyzing sections of phases, followed by the approximation of the contours of the structural components using the Freeman chain [15]. According to which the analytic dependence which describes the contour of the image is presented by set of parametric equations based on Fourier series. The determination of the thermophysical properties of the material was carried out according to the following algorithm: 1) using the SHAPE software (the ChainCoder module for randomly selected grains from structure images, their Freeman chain codes were determined and the contour reconstruction was carried out; 2) using the SHAPE module CNC2NEF, grains centers of mass, largest radii and Fourier coefficients of each grain for 50 harmonics were found; 3) arithmetic mean of the Fourier coefficients for the set of carbide grains was used to find mean shape of the grain and built three dimensional model of the structure; 4) modelled structure was analyzed using the Digimat 6.1 software to determine the thermophysical properties of the mechanical sealing rings material by the Mori-Tanaka algorithm [16].

The process of heat transfer during friction contact interaction of the rings was described by a scheme shown in figure 8 in which two half-infinite rods of the same radius size, but with different thermophysical properties, are in contact with a source with a specific energy $q(t)$ ($J/s \cdot cm^2$).
Figure 8. Calculation scheme of the heat flow during friction of mechanical sealing rings.

The surface heat transfer of the rods along the length was taken into account by negative $W_i$ sources, which were written as:

$$c_i \rho_i \frac{\partial T_i(x,t)}{\partial t} = \lambda_i \frac{\partial^2 T_i(x,t)}{\partial x^2} - W_i, \quad (i = 1, 2),$$

where $\lambda$ – thermal conductivity, W/cm·°C; $c$ – specific heat, J/gK; $\rho$ – density g/cm$^3$. The sources of $W_i$ express the amount of heat that is deducted from the volume unit (J/s·cm$^3$) for the $2l$ length of the contact will be:

$$W_i = \frac{2\alpha T(x,t)}{l},$$

where $\alpha$ – coefficient of heat exchange, W/m$^2$·°C. After substituting into equation (1) we obtain:

$$c_i \rho_i \frac{\partial T_i(x,t)}{\partial t} = \lambda_i \frac{\partial^2 T_i(x,t)}{\partial x^2} - \frac{2\alpha T(x,t)}{l}.$$ (3)

As a result, the mathematical formulation of the original problem will have the form:

$$\frac{\partial T_1(x,t)}{\partial t} = a_1 \frac{\partial^2 T_1(x,t)}{\partial x^2} - b_1 T_1(x,t), \quad -\infty < x < 0;$$

$$\frac{\partial T_2(x,t)}{\partial t} = a_2 \frac{\partial^2 T_2(x,t)}{\partial x^2} - b_2 T_2(x,t), \quad 0 < x < \infty,$$

where the following notation is entered:

$$a_i = \frac{\lambda_i}{c_i \rho_i} \quad \text{and} \quad b_i = \frac{2\alpha}{c_i \rho_i l}.$$ (4)

The boundary conditions that determine the conditions for the continuity of the temperature field and the heat exchange on the contact surfaces for the solution of the problem will have the form:

$$T_1(x,0) = T_2(x,0) = 0; \quad T_1(0,t) = T_2(x,t)$$

$$\lambda_1 \frac{\partial T_1(0,t)}{\partial x} - \lambda_2 \frac{\partial T_2(0,t)}{\partial x} = q(t).$$ (5)

After solving origin task using operational analysis, we obtain the solution in the form of following equations:
\[
T_1(-z,t) = \frac{q_0 K_e}{2 \lambda_1 (K_x + 1)} \sqrt{a_1/b} \times \\
\times \left[ \exp \left( -\frac{b}{\sqrt{a_1}} \right) \text{erfc} \left( \frac{z}{2 \sqrt{a_1 t} - \sqrt{b t}} \right) - \exp \left( -\frac{b}{\sqrt{a_1}} \right) \text{erfc} \left( \frac{z}{2 \sqrt{a_1 t} + \sqrt{b t}} \right) \right],
\]

\[
T_2(x,t) = \frac{q_0 \sqrt{a_2}}{2 \lambda_2 (K_x + 1)} \sqrt{a_2/b} \times \\
\times \left[ \exp \left( -\frac{b}{\sqrt{a_2}} \right) \text{erfc} \left( \frac{x}{2 \sqrt{a_2 t} - \sqrt{b t}} \right) - \exp \left( -\frac{b}{\sqrt{a_2}} \right) \text{erfc} \left( \frac{x}{2 \sqrt{a_2 t} + \sqrt{b t}} \right) \right],
\]

where

\[
K_x = \frac{\lambda_1 \sqrt{a_2}}{\lambda_2 \sqrt{a_1}}.
\]

In the dry friction condition of the mechanical seal rings \( q_0 = Q/F \). Here \( Q \) (J/s) is the heat generated during friction [2]:

\[
Q = p \mu v_m F,
\]

where \( v_m \) – average speed, \( \mu \) – coefficient of friction, \( F \) – contact area, \( p \) – contact pressure.

4. Results and discussion

Results of microstructural SEM investigations of proposed mechanical sealing ring composite metal-ceramic material together with XRD analysis show that its structure consists of three main phases, namely higher chromium carbide \( \text{Cr}_3\text{C}_2 \), complex chromium-manganese carbide \((\text{Cr,Mn})_7\text{C}_3\) and Cu-based solid solution of Ni and Mn. The average size of the carbide grains is \( \approx 5 \mu m \) as it shown in figure 9 and its volume content is approximately 65%. Results of the EDS analysis across the carbide-matrix interfaces shows, that the width of interdiffusion zone is less than 0.2 \( \mu m \), so its impact on thermo-physical characteristics was excluded from simulations. After averaging out of the shape factors values for 21 randomly selected grains, the mean contour of the grains of the carbide phase was obtained. Considering that the average contour has a rounded elongated shape of the image of a carbide particle of mean shape in a three-dimensional coordinate system was obtained by rotating the contour around the axis on which the largest distance measured from the center of mass was located. The particulate reinforced metal matrix composite structure was generated by distribution the carbide grain with mean shape into a three-dimensions using the Digimat 6.0.1 software. The homogenization of it, based on the Mori-Tanaka algorithm, taking into account the characteristics of the matrix and the carbide phase, allowed the integral thermophysical characteristics, which are necessary for the determination of heat transfer calculations during friction interaction of mechanical sealing rings.
Figure 9. Stages of modelling metal-ceramic composite material structure for mechanical sealing rings.

After substituting the values of the thermophysical characteristics of the materials of the rings ($\lambda = 1.2$ W/cm·°C; $a = 0.077$ cm$^2$/s; $b = 0.004$ l/s for SiC and $\lambda = 1.46$ W/cm·°C; $a = 0.034$ cm$^2$/s; $b = 0.004$ l/s for Cr$_3$C$_2$-Cu60-Ni20-Mn20) and the measured values of the dry friction coefficients, the dependences of the temperature distribution on the cross sections of the rings depending on the distance to the contact area for the given time point were obtained. The value of convective heat transfer coefficient (for low-speed air flow) was set equal to 12 W/m$^2$K, according to [17]. As can be seen from the temperature distribution dependencies shown in figures 10 and 11, temperature stabilization in both friction pairs begins after 400 s of friction. At the same time, for the SiC – SiC rings pair, the maximum temperature in the contact zone is ~ 180 °C, which is almost 2 times higher than the temperature in the SiC – Cr$_3$C$_2$-Cu60-Ni20-Mn20 contact zone. This is because of decreasing in the coefficient of friction caused by the presence in the contact zone of the plastic phase (manganese cupronickel), which acts as solid lubricant due to the formation on the contact surfaces of a protective antifriction film containing the oxide phases of Mn, Cu and Ni.

Figure 10. Temperature distribution in SiC – SiC friction pair ($\mu = 0.23$).

Figure 11. Temperature distribution in SiC – Cr$_3$C$_2$-Cu60-Ni20-Mn20 friction pair ($\mu = 0.12$).
Comparison of the results of calculations based on the developed mathematical model and the data obtained on the basis of experimental studies shows that the developed mathematical model with sufficient accuracy (for engineering calculations) describes the process of heat distribution in the conditions of dry friction of the mechanical seals as can be seen in figure 12.

Figure 12. Kinetics of contact temperature grown for ceramic (SiC) – metal-ceramic (Cr$_3$C$_2$ – Cu60-Ni20-Mn20) pair during dry friction.

The tribotechnical tests were carried out by determination the friction coefficient of the studied pairs at temperature - the main factor affecting the wear process as a result of changing the sliding speed, which imitates the work of the real mechanical seal. From the obtained dependencies shown in figure 13, it can be concluded that increasing sliding speed up to 1 m/s leads to the increasing of friction coefficient, during further increasing of the sliding speed above 1 m/s friction coefficient shows tendency to decrease and then stabilizes at ~ 0.25 and ~ 0.12 for SiC – SiC and SiC – Cr$_3$C$_2$ – Cu60-Ni20-Mn20 pair, respectively. Extreme values of friction coefficients for investigated ring materials combinations correspond to different sliding speed. This is caused by different nature of surface layer substructure formation. In the SiC – SiC friction pair at high sliding speed the formation of silicon oxide phases on contact surfaces takes place. Their presence due to formation of the "third body" in the friction zone reduce the coefficient of friction. At the same time, in a SiC – Cr$_3$C$_2$-Cu60-Ni20-Mn20 friction pair at high sliding speed (above 2 m/s), the surface of the metal-ceramic ring retains a metallic luster. Such change in the state of the surface layer can be explained by the processes of separation and plasticization of the metal bond, which is evenly distributed over the friction surfaces. Under these conditions, a surface layer appears on the surface, which allows to reduce the friction coefficient. Results of microscopic investigations and chemical analysis of the surfaces of ceramic (SiC) rings after tribological tests show the presence of thin surface layers enriched with copper as shown in figure 14. This indicates the friction-induced mass transfer of binder-alloy from metal-ceramic composite to a surface of ceramic counter body, which promotes significantly improving of the antifriction properties due to solid lubrication.
Industrial testing of the proposed materials of sealing rings combination in mechanical seals were performed in liquid propane pumping conditions, using centrifugal pumps of 4NG5x2 type, which are the part of gas fractionation unit shown in figure 15. According to its results after the replacement of a pair of ceramic sealing rings from silicon carbide on a combination of metal ceramics (Cr2C2 - Cu60–Ni20–Mn20) - ceramics (SiC), the durability of the results of the planned inspection increased by 2 times compared with the serial ones.

5. Conclusions
Metal-ceramic composite materials based on higher chromium carbide (Cr2C2), obtained by infiltration porous carbide preforms with manganese cupronickel (Cu60–Ni20–Mn20) melt are perspective materials for manufacturing mechanical sealing rings of centrifugal pumps due to its extremely high resistance to thermal cracking and rather high thermal conductivity in comparison with ceramic materials. Replacement of the ceramic (SiC) - ceramic (SiC) rings of friction pairs of mechanical seals
with metal-ceramic (\(\text{Cr}_3\text{C}_2 - \text{Cu}60 - \text{Ni}20 - \text{Mn}20\)) – ceramic (SiC) ones almost completely prevents brittle failure of the sealing surfaces in the initial stages of pump running.

References

[1] Jane Wang Q and Yip-Wah 2013 *Encyclopedia of tribology* (New York: Springer-Verlag) p 4139
[2] Mayer E 1977 *Mechanical seals* (London: Newnes-Butterworth) p 291
[3] Alan O. Lebek 1991 *Principles and design of mechanical face seals* (New York: Wiley-Interscience) p 764
[4] Müller H K and Nau B S 1998 *Fluid Sealing Technology: Principles and Applications* (New York: Marcel Dekker, Inc.) p 485
[5] Shankar L and Kumar P K 2017 *Mechanics & Industry* 18 115
[6] Nau B S 1997 *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* 211 165
[7] Ahmed Yu H and de Villiers Lovelock H. 2007 *Journal of Tribology* 129 586
[8] Song S, Lu B, Gao Z, Bao C, Ma Y 2019 *Ceramics International* 45 17987
[9] Kim Y H and Kim Y W 2019 *Journal of the European Ceramic Society* 39 4487
[10] Engqvist H, Botton G A, Ederyd S, Phaneuf M, Fondelius J and Axen N 2000 *International Journal of Refractory Metals and Hard Materials* 18 39
[11] Prysyazhnyuk P M, Shihab T A and Panchuk V H 2016 *Mater. Sci. 52* 188
[12] Prysyazhnyuk P, Lutsak D, Vasylyk A, Shihab T and Burda M 2015 *Metallurgical and Mining Industry* 12 346
[13] Shlapak L S, Shikhab T, Prisyazhnyuk P N and Yaremiy I P 2016 *Metallofizika i Novejshee Tekhnologii* 38 969
[14] Gamsonov G 1980 *Handbook of Refractory Compounds* (New York: Springer US) p 556
[15] Iwata H, Ukai Y 2002 *J. Hered.* 93 384
[16] Mori T, Tanaka K 1973 *Acta Mater.* 21 571
[17] De Saracibar C A, Chiumenti M, Cervera M, Dialami N and Seret A 2014 *Archives of Computational Methods in Engineering* 21 3