UDC 541.11/123(015.8)
DOI https://doi.org/10.52171/herald.381

Investigation of Tribocracking Processes during the Frictional Interaction of Metal-Polymer Friction Pairs

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Abstract

This article presents a developmental design of a device for studying tribocracking processes in metal-polymer friction pairs and proposes a corresponding research method. The study found that an increase in surface-volume temperature enhances the formation of endothermic reaction products from the polymer lining's upper layer, raising the equilibrium constant and releasing heat. According to Van 't Hoff's principle, elastic-plastic deformation occurs in the microprotrusions of the metal surface. Conversely, lowering the surface temperature intensifies exothermic reactions with ion dissociation in the polymer layer. Pulsed specific loads on microprotrusion contact patches reduce the release of gaseous products, including unsaturated hydrocarbons that react with hydrogen, and these loads depend directly on the local dynamic coefficient of mutual overlap. Operating parameters of the tribocracking phenomenon were obtained using the test device. The proposed method and device allow prediction of energy load, polymer and metal weight losses, and gas mixture composition. Additionally, they enhance functionality, improving the informativeness of tribological studies and reliability of results, enabling rational selection of existing materials for friction pair components and facilitating the development of new materials. Overall, the device and method provide a systematic approach to analyzing friction-induced tribocracking, linking mechanical and chemical interactions in metal-polymer pairs under varying thermal and load conditions.

Keywords: device and research method; metal-polymer friction pair, surface-volume temperature, cracking phenomena

Submitted *29 September 2025*
Published *16 March 2026*

For citation:
A.Kh. Janahmadov et al.
[Tribocracking Processes During Frictional Interaction of Metal-Polymer Friction Pairs]
Herald of the Azerbaijan Engineering Academy, 2026, vol. 18 (1), pp. 20-30
ISSN (p): 2076-0515, ISSN (e): 2789-8245

Azərbaycan Mühəndislik Akademiyasının Xəbərləri
2026, cild 18 (1), s. 20-30
Ə.X. Canəhmədov və b.

Herald of the Azerbaijan Engineering Academy
2026, vol. 18 (1), pp. 20-30
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Metal-polimer sürtünmə cütlərinin friksion qarşılıqlı təsiri zamanı tribokrekinq proseslərinin tədqiqi

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Xülasə

Məqalədə metal-polimer sürtünmə cütləri arasında tribokrekinq proseslərinin tədqiqi üçün təcrübi-konstruktor qurğusu təqdim olunub və bu qurğuya əsaslanaraq tədqiqat metodu təklif edilib. Tədqiqat nəticəsində aşağıdakılar müəyyən edilib: səthi-həcmi temperaturun artması polimer kündənin üst qatından ayrılan endotermik reaksiyanın məhsullarının həcmində və müvazinətdəki sabitlikdə artıma səbəb olur ki, bu da istilik ayrılmasına səbəb olur. Van't Hoff prinsipinə uyğun olaraq, metal səthindəki mikroçıxıntılar elastik-plastik deformasiya olunur. Səthi temperaturun azalması isə polimer səthində ionların disosiasiyası ilə ekzotermik reaksiyanı gücləndirir. Mikroçıxıntı kontakt nöqtələrində impulsvari spesifik yüklərin artması qaz məhsullarının, o cümlədən hidrogenlə birləşən doymamış hidrokarbonların ayrılmasını azaldır və bu yük lokal dinamik örtük əmsalına birbaşa bağlıdır. Krekinq fenomeninin əməliyyat parametrləri sınaq qurğusu vasitəsilə müəyyən edilib. Təklif olunan metod və qurğu enerji yükünü, polimer-metal komponentlərinin kütlə itkilərini və əmələ gələn qaz qarışığının tərkibini proqnozlaşdırmağa imkan verir. Bundan əlavə, metod triboloji tədqiqatların məlumatlandırıcılığını artırır, sınaq nəticələrinin etibarlılığını təmin edir, mövcud materialların rasional seçimini və yeni materialların hazırlanmasını mümkün edir.

Açar sözlər: qurğu və tədqiqat metodu, metal-polimer sürtünmə cütü, səthi-həcmi temperatur, krekinq fenomeni

Исследование процессов трибокрекинга при фрикционном взаимодействии металлополимерных пар трения

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Аннотация

В статье представлена опытно-конструкторская разработка устройства для изучения процессов трибокрекинга в металлополимерных парах трения и предложен соответствующий метод исследований. Исследование показало, что повышение поверхностно-объемной температуры увеличивает выделение продуктов эндотермических реакций из верхнего слоя полимерной накладки, повышает константу равновесия и сопровождается выделением тепла. В соответствии с принципом Вант-Гоффа происходит упругопластическая деформация микровыступов металлической поверхности. Снижение температуры поверхности усиливает экзотермическую реакцию с диссоциацией ионов в полимерном слое. Рост импульсных удельных нагрузок на пятнах контактов микровыступов уменьшает выделение газообразных продуктов, включая ненасыщенные углеводороды, соединяющиеся с водородом; при этом нагрузки напрямую зависят от локального динамического коэффициента перекрытия. Эксплуатационные параметры явления крекинга определены с помощью испытательного устройства. Предложенный метод и устройство позволяют прогнозировать энергонагруженность, потери массы полимерных и металлических компонентов, а также состав образовавшейся газовой смеси. Кроме того, они расширяют функциональные возможности, повышают информативность трибологических исследований и достоверность результатов, обеспечивают рациональный подбор существующих материалов и способствуют разработке новых.

Ключевые слова: устройство и метод исследований; металлополимерная пара трения, поверхностно-объемная температура, явления крекинг

Introduction

In tribology, three sequential and interrelated friction processes have been formulated: frictional interaction of contact patches (ohmic, neutral, and blocking) of microprotrusions of rubbing surfaces, changes in the properties of surface and subsurface layers as a result of this interaction, and surface failure as a result of the two preceding stages. These friction stages occur in the following fields: mechanical, electrical, thermal, chemical, and corrosion. The driving force is the oxidation-reduction potential and its gradients.

Any stable structural-phase state exists for a short period of time, transitioning to a new level of instability due to processes, phenomena, and effects that increase the overall entropy and, accordingly, decrease the free energy of materials. This triggers a subsequent transition to a new quasi-stable state. The process continues for a certain period of time, determined by the physicochemical properties of the corresponding transformations, and the ability to create conditions under which these transitions occur with as little periodicity as possible.

Analysis of sources and the state of the problem. In [1, 2], a simple fractional differential equation is used to describe the kinetics of thermo-oxidative degradation of polymers in the auto-retarded mode. This equation is analogous to the description of the positron annihilation process [2], which allowed the introduction of a fundamentally new postulate: only a portion of the polymer coil, determined by its fractal structure, undergoes oxidation.

To describe the kinetic curves of thermooxidative degradation of polymeric materials, fractional differential equations with a right-hand side dependent on the order of the oxidation reaction are presented. It is shown that thermooxidative degradation is only possible in the case of a fractal polymer structure. For both autoretarded and autoaccelerated kinetic curves, the order of the derivative in the equation coincides with the fraction of the remaining part of the polymer macromolecular coil [3].

Article [4] provides an analysis and synthesis of thermoelectric processes characterizing the electrothermomechanical frictional interactions of friction pairs in brake assemblies. The top layer of the polymer lining is isolated at temperatures above the permissible limits for its material, when the cracking process occurs.

Thermokinetic models of the interaction of a metal friction element operating in various environments are examined. The influence of surface and bulk temperatures, pulsed specific loads, the coefficient of mutual friction pair overlap, the ratio of reactant amounts, the presence of inert gases, and the type of reaction on the rate of chemical reactions during the cracking process in the upper layer of polymer linings of brake friction units is established. It is shown that when assessing the equilibrium of a chemical reaction, it is necessary to consider the change in Gibbs free energy.

A device for studying friction processes is known, comprising: a housing, a cylindrical specimen holder mounted in it on bearing supports, a drive for rotating the cylindrical specimen holder, a cylindrical specimen, a counter-specimen in the form of an overlay, a unit for creating a normal load between the working surfaces of the cylindrical specimen and the counter-specimen. In addition, the device has sensors for determining the magnitude of the friction force during the test [5-7].

This device has a significant drawback, as it only allows for the determination of parameters such as wear and friction force during research. However, this information is insufficient to assess the processes occurring between interacting components. Microprotrusions of surfaces, and to establish the mechanism of destruction of the surface layers of elements of metal-polymer friction pairs [8-11].

The purpose of the work

The purpose of this work is to propose a method for studying tribocracking processes during frictional interaction in metal-polymer friction pairs and a device for implementing this method.

A device for studying tribocracking during frictional interaction of metal-polymer friction pairs. The device (Fig. 1 a, b and 2 a, b, c, d) comprises a housing 1, a holder 2 of a cylindrical metal specimen 3 mounted therein on bearing supports, a drive for rotating the holder 2 with a given angular velocity ω , as well as the cylindrical metal specimen 3 with a working outer cylindrical surface 4, a counter-specimen 5 made of a polymer material in the form of a lining and having radial through (stepped) holes 6 on the side of the working inner cylindrical friction surface 7 for collecting wear products and a radial load means 8 between the working surfaces 4 and 7, respectively, of the cylindrical metal specimen 3 and the polymer counter- specimen 5. The surface temperature in the friction zone is measured by a thermocouple 9 connected to a micropotentiometer 10.

The device also comprises a gas analyzer 11, a vacuum pump 12 which serves to pump out gases generated during the friction process of the working surfaces of the elements of the metal-polymer pair, switching gas distribution valves 13, gas pipelines 14 and a collector ring 15. The latter is made of an antifriction material, for example, fluoroplastic and is mounted coaxially with the axis of rotation of the holder 2 of the metal cylindrical sample 3 and interacts with its working end surface 16 with the working end surface 17 of the sample 3 and carries out only axial movement. Means for axially pressing 18 of the collector rings 15 to the working end surface 17 of the cylindrical metal sample 3 with a force F that ensures sealing of the joint between the said working end surfaces 16 and 17, similar to that in an end seal. Therefore, the specified working end surfaces 16 and 17 must be pre-lapped.

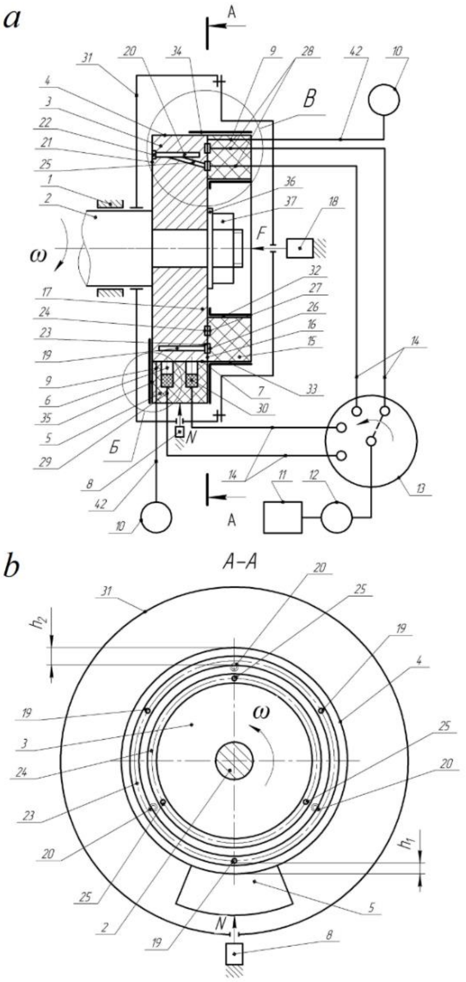

Figure 1 a, b – General view of the testing device (a) and its cross-section along A-A (b)

In the body of the cylindrical metal sample 3, at least two groups of axial blind holes 19 and 20 are made on the side of its end surfaces 17 and 21, respectively, the axes of which are parallel to the axis of rotation of this cylindrical metal sample 3 and are uniformly located in circles, the centers of which coincide with the said axis of rotation. Each of these groups of axial blind holes 19 and 20 is located at a different depth h1 and h2 from the working outer cylindrical surface 4 of the said metal sample 3. In this case, axial blind holes 20, made on the side of the non-working end surface 21 of the cylindrical metal sample 3, are plugged with threaded plugs 22.

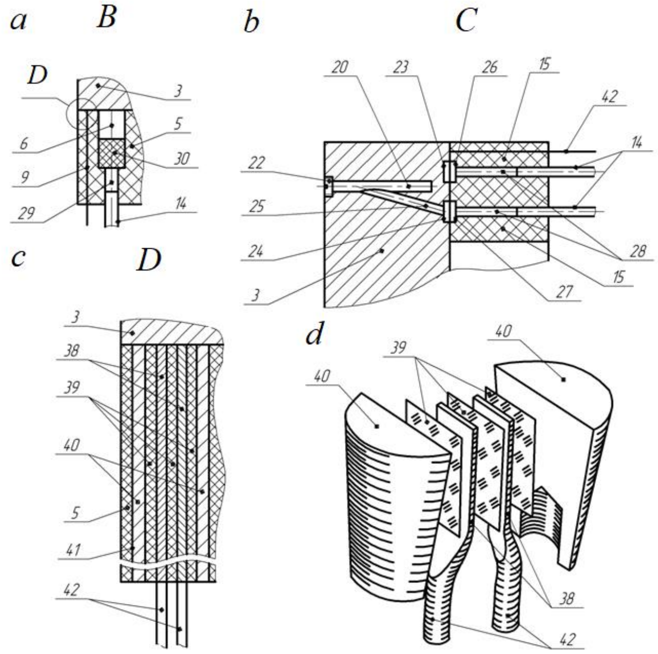

Figure 2 a, b, c, d – Local views B, C, D (a, b, c) of the test device elements and the design of a tape thermocouple (d)

In addition, annular concentric grooves 23 and 24 are made on the working end surface 17 of the cylindrical metal sample 3. The location of the annular concentric groove 23 coincides with the axial blind holes 19, and the annular concentric groove 24 along the system of inclined channels 25, connected to the corresponding group of axial blind holes 20. On the working end surface 16 of the collector ring 15, annular concentric grooves 26 and 27 are also made, corresponding to the annular concentric grooves 23 and 24 on the working end surface 17 of the metal cylindrical sample 3.

It is possible to design the device in such a way that the cylindrical metal sample 3 will have more than two groups of axial blind holes located at different distances from its working outer cylindrical surface 4. In this case, the number of annular concentric grooves on the working end surface 17 of the metal cylindrical sample 3 and on the working surface 16 of the collector ring 15 will increase accordingly.

In the collector ring 15, from the depressions of the annular concentric grooves 26 and 27, lateral through holes 28 are made, which are connected to the gas analyzer 11 through the gas pipelines 14, the switching gas distribution valves 13 and the vacuum pump 12. In the body of the polymer counter-sample 5 there are through radial (stepped) holes 6, passing into holes of smaller diameter 29, with filters 30 installed in them made of porous solid materials, which, in turn, are also connected to the gas analyzer 11 through the gas pipelines 14, the switching gas distribution valves 13 and the vacuum pump 12.

The metal-polymer friction pair under study: the working outer cylindrical surface 4 of the metal cylindrical specimen 3, the polymer counter-specimen 5, and the collector ring 15 are housed in a stationary, sealed housing 31, which is disassemblable in two parts for ease of installation. To seal the movable joints between the aforementioned friction pairs, additional sealants 32–35 are also used, respectively. Cylindrical metal specimen 3 is securely fastened to holder 2 using washer 36 and nut 37.

To measure temperatures in friction pairs: the working outer cylindrical surface 4 of the cylindrical metal sample 3 – the counter-sample 5, as well as the working end surface 17 of the metal sample 3 – the working end surface 16 of the collector ring 15, tape thermocouples 8 are used. The latter has thermoelectrodes 38 made of chromel (+) and copel (–). Between said thermoelectrodes 38, insulating layers 39 are located. Thermoelectrodes 38 together with insulation layers 39 are placed in housing 40. In assembled form, thermocouples 9 are installed in conical holes 41, which are made in counter-sample 5 and in collector ring 15. Terminals 42 of thermocouples 9 are connected to micropotentiometers 10 (Fig. 2).

The system for measuring the volume of gases and liquids formed during testing of a metal-polymer friction pair is not shown.

Device During operation it works as follows.

For testing, cylindrical metal samples 3 They are made from various materials, including those with protective coatings, such as chromium, and those deposited, for example, using high-temperature self-propagating synthesis. Counter-specimens 5 are made from different grades of polymeric materials. Before testing, metal cylindrical specimen 3 and polymer counter-specimen 5 are degreased, dried, and weighed.

After this, the cylindrical metal sample 3 is installed on the holder 2 and fixed in place using the washer 36 and nut 37. The counter-sample 5 is correspondingly fixed in its holder.

Holder 2 is set in rotation at a given angular velocity ω. Frictional interaction occurs between the working end surface 17 of metal cylindrical sample 3 and the working end surface 16 of collector ring 15 in the contact zone, resulting in a certain background gas evolution – a systematic experimental error. This gas evolution is recorded by gas analyzer 11 and taken into account in further studies.

After this, using the radial load 8, a radial load specified by the test program is applied to the counter-sample 5, made in the form of a polymer overlay, N facilitating the frictional interaction of its working cylindrical surface 7 with the working surface 4 of the cylindrical metal sample 3. The standard means of the friction and wear machine are used to record and determine the main tribological parameters of the process: the dynamic coefficient of friction; the amount of wear of the friction pair elements; etc.

Since the process of friction in metal-polymer pairs causes the processes of gas separation and diffusion of gases, in particular hydrogen, into the depth of the metal of the cylindrical sample 3, these gases are collected by groups of blind axial holes 19 and 20 from different depths h_1, h_2 the size of which is determined by the distance from the working outer cylindrical surface 4 of the cylindrical metal sample 3 to the generators of these blind axial holes 19 and 20. From the axial blind holes 19, the gas medium is pumped out through the cavity formed by the connected annular concentric grooves 23 and 26, and then through the lateral through holes 28 in the collector ring 15, the gas pipeline 14, the switching gas distribution valves 13 and through the vacuum pump 12 to the gas analyzer 11. When the said switching gas distribution valves 13 are correspondingly turned on, the gases entering the gas analyzer 11 are pumped out and analyzed. from a certain group of holes located at different depths from the working outer cylindrical surface 4 of the metal sample 3.

The gas collected from the group of axial blind holes 20, which are plugged with threaded plugs 22 on the side of the non-working end surface 21, enters through the system of inclined channels 25 into the cavity formed by the annular concentric grooves 24 and 27, respectively, and then, as in the previous case, to the gas analyzer 11.

The gaseous medium formed directly in the intercontact friction volume between the working cylindrical surface 4 of the metal sample 3 and the working surface 7 of the polymer counter-sample 5 is pumped out by a vacuum pump 12 through through radial (stepped) openings 6 and 29, respectively. In this case, the gas passes through a filter 30 installed in the through (stepped) opening 6, a gas pipeline 14, switching gas distribution valve 13, and then it is fed into gas analyzer 11 by vacuum pump 12.

The device allows for the analysis of the composition of gases formed as a result of friction and diffusing deep into the metal of a cylindrical metal sample 3, as well as the determination of the volumes of these gases. Radial through (stepped) holes 6 in the polymer counter sample 5, also serve to select solid wear products that form during tribological testing.

This is how studies of tribocracking processes are carried out during frictional interaction in metal-polymer friction pairs: the working outer cylindrical surface 4 of the metal sample 3 – the working inner cylindrical surface 7 of the polymer counter-sample 5 at different temperatures during testing, including at the permissible surface temperature of the polymer material of the counter-sample 5.

To understand the mechanism of operation of the polymer material of counter-sample 5 in the permissible temperature zone and above, let us consider the derivation diagram sample of friction material FK-24A, obtained by academician A.Kh. Janahmadov (see Fig. 3).

Friction materials for brake devices should be studied from the standpoint of the physicochemical mechanics of friction under braking conditions using thermogravimetric and differential thermal analysis methods. The results of these studies for a sample of FK-24A material are presented in Fig. 3. It was found that thermal destruction of the FK-24A sample begins at a temperature of 300 °C. The calculated activation energy for the decomposition of the FK-24A sample was 85.5 kJ/mol. It was proven that the sample decomposes within 15 minutes when maintained at a temperature of 400 °C. The rate of its mass loss increases with a further increase in temperature. It should be noted that the modes of studying the thermal -stability of the FK-24A material in the form of a sample do not always fully correspond to the actual operating conditions of the near-surface layers of friction linings in friction pairs of brake devices.

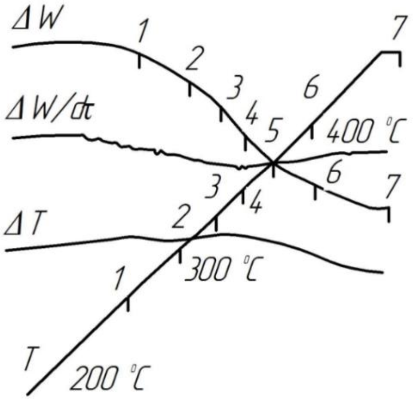

Figure 3 – Dependence of the derivatogram of the FK-24A sample on the temperature and time of the processes: ΔW – mass loss determined by the thermogravimetric curve; ΔW / dτ – rate of change (differential-thermographic curve); ΔT – differential-thermal curve; t – temperature; τ – time

The destruction of friction materials is accompanied by intense smoking, followed by the formation of liquid fractions in the pores of their surface layer. Adsorbent molecules are very firmly held in the micropores of the material's surface layer due to their being surrounded by a large number of carbon atoms. Gas-phase adsorption is a condensation process that occurs when the adsorption energy is sufficient to condense the vapor. The condensed vapor remains in the porous structure of the carbon as a liquid.

Thus, from the above it follows that the saturated steam formed from moisture and water on the working internal cylindrical friction surface 7 of the polymer counter-sample 5 will move in the same way as the gaseous mixture during pumping by the vacuum pump 12, ultimately getting into the gas analyzer 11.

The arrangement of the friction pair under study: the working outer cylindrical surface 4 of the metal specimen 3 – the working inner cylindrical surface 7 of the polymer counterspecimen 5 in a sealed housing 31 ensures testing in a controlled environment (gas, vapor, or liquid, including electrolyte). Said sealed housing 31 is mounted immovably on the device and, for ease of installation, is disassemblable in two parts.

The weight loss of the lining is determined based on the results of weighing samples 3 and 5 before and after tribological testing.

The tribocracking processes were investigated during the frictional interaction of the elements of a metal-polymer friction pair: the working outer cylindrical surface 4 of a metal sample 3 – the working inner cylindrical surface 7 of a polymer counter-sample 5. The cylindrical steel sample 5 was given rotation, and the polymer was pressed against it with its working inner cylindrical surface 7. Counter-sample 5 was used to monitor the temperature in the friction zone and analyze the resulting wear debris. The temperature in the metal-polymer friction pair was measured using a strip thermocouple 9, mounted in the body of polymer counter-sample 5, which was connected via terminals 42 to a micropotentiometer 10. Vacuum pump 12 and gas-vapor analyzer 11 were simultaneously turned on, and the chemical composition of the gas mixture was determined using its readings, while the volumetric parameter was determined using a flow meter. The amount of water pumped out of the frictional interaction zone of the friction pair elements was determined from the graduations of the measuring tube.

Research method and results

The method for studying tribocracking processes during frictional interaction in metal-polymer friction pairs includes the following operations:

– degreasing, drying and weighing the cylindrical metal sample and polymer counter sample;

– rotation of a cylindrical metal specimen around an axis. Two groups of axial blind holes are made in the body of the cylindrical metal specimen at different depths from the working outer cylindrical surface on the side of its end surfaces, the axes of which are parallel to the axis of rotation of the cylindrical metal specimen and are uniformly spaced in circles, the centers of which coincide with the said axis of rotation;

– pressing with a given radial load against the working outer cylindrical surface of a metal specimen by the working inner surface of a counter-specimen, made of a polymeric material in the form of an overlay and having radial through holes on the side of the cylindrical friction surface, in which filters made of solid porous materials are installed.

– The magnitude of the load ensures that the permissible surface temperature of the polymeric material of the counter-specimen is achieved during testing of the metal-polymer friction pair;

– control of surface temperature in a metal-polymer friction pair;

– pumping out gases formed during the friction process from each radial through hole in the polymer counter-sample using a vacuum pump separately and each axial blind hole in the cylindrical metal sample separately, which penetrated the metal, through the lateral through holes from the collector ring, which is made of antifriction material and is installed coaxially with the axis of rotation of the said cylindrical metal sample and interacts with its working surface with the working surface of the cylindrical metal sample;

– collection of gaseous and solid wear products formed during the interaction of the elements of the metal-polymer pair and accumulating in the radial through holes of the counter-sample, in which filters made of solid porous materials are installed (separately from each specified hole), as well as collection of gaseous wear products separately from each axial blind hole in the metal cylindrical sample, which have penetrated through the metal;

– conducting control and analysis of the formed solid and gaseous wear products, selected separately from each radial through hole of the polymer counter-sample, in which filters made of solid porous materials are installed, and the formed gaseous wear products selected separately from each axial blind hole in a cylindrical metal sample that has penetrated the metal;

– determination of the weight loss of the lining based on the results of weighing the samples before and after testing.

The metal-polymer friction pair was tested at the following temperatures in the friction interaction zone for the experiments: No. 1 – t = 150 ºC; No. 2 – t = 215 ºC; No. 3 – t = 420 ºC; No. 4 – t = 500 ºC; No. 5 – t = 730 ºC.

The results of experimental studies of changes in the quantity and composition of the gas mixture formed in a metal-polymer pair indicate that the process of friction and wear of the elements of a metal-polymer friction pair: 30KhGSA steel – FK-24A polymer material has a complex tribochemical nature (Table).

The volume of water collected in the measuring tube was 3.54 milliliters.

An analysis of the research results presented in Table 1 showed that with an increase in temperature in the zone of the metal-polymer friction pair, the hydrogen content in the gas mixture also increases (experiment № 2 - № 5).

Table – The percentage ratio of the components of the gas mixture formed in the intercontact volume of the metal-polymer friction pair

Experiment number	Brand of polymer material	Temperature, ºC	Gas content, %						
			H_2	B_2	N_2	CO_2	CO	$\sum C_nH_m$	Other gases***
1	FK-24A	150	*	19.8	78.8	0.28	*	*	Rest
2	FK-24A	215	0.050	19.8	78.8	0.23	*	*	
3**	FK-24A	420	0.123	19.1	79.5	0.13	*	*	
4**	FK-24A	500	0.171	16.3	81.6	0.24	0.24	0.24	
5	FK-24A	730	0.308	9.8	81.2	0.08	0.08	1.06	

Note: ** presence of traces of the specified gases;*
*** Sampling was carried out from four zones (points) simultaneously;*
**** Other gases include: Ar, Ne, He, Kr, Xe, Rn, O_2, N_2O.*

Discussion of Results

The experimental design of a device for studying tribocracking processes during frictional interactions between metal-polymer friction pairs, and a proposed research method based on this device, allowed us to establish the following:

- in the surface-volume temperature promotes an increase in the volume of endothermic reaction products released from the upper layer of the polymer lining, as well as an increase in the equilibrium constant, which is accompanied by the release of heat. In accordance with the Van 't Hoff principle of dynamic equilibrium, elastic-plastic deformation of the microprotrusions of the working surface of the metal friction element occurs. A decrease in the surface temperature of the friction pairs promotes an intensification of the exothermic reaction with the dissociation of ions in the surface layer of the polymer lining;
- an increase in the pulse specific loads on the contact spots of microprotrusions in a friction pair leads to a decrease in the release of gaseous products, including unsaturated hydrocarbons that combine with hydrogen, from their inter-contact gap; in this case, the pulse specific loads in friction pairs directly depend on their local dynamic coefficient of mutual overlap;
- the operational parameters of the cracking phenomenon were obtained using a test device.

Conclusion

Thus, a method for studying tribocracking processes during frictional interaction in metal-polymer friction pairs and a device for implementing it have been proposed. These methods enable prediction of not only their energy loading and weight losses of polymer and steel friction pair components, but also the composition of the resulting gas mixture. Furthermore, they provide expanded functionality, thereby increasing the informativeness of tribological studies and the reliability of test results, enabling both the rational selection of existing materials for metal-polymer friction pair components and the development of new materials.

Conflict of Interests

The authors declare there is no conflict of interests related to the publication of this article.

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