Problems of Tribology, V. 28, No 3/109-2023,56-63

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2023-109-3-56-63

Detection of changes in the characteristics and properties of friction zones of parts of tribocoupling systems and machine assemblies based on the entropy approach

V.V. Aulin, A.A. Tykhyi, O.V. Kuzyk, S.V. Lysenko, A.V. Hrynkiv, I.V. Zhylova

Central Ukrainian National Technical University, Ukraine
E-mail: AulinVV@gmail.com

Received: 05 September 2023: Revised:25 September 2023: Accept:30 September 2023

Abstract

The role of entropy in the processes of friction and wear of tribocoupling materials of moving parts is clarified. The implementation of the effect of self-organization of materials depending on the production of entropy is theoretically substantiated. The conditions of self-organization with negative entropy production were obtained. The relationship between the rate of volumetric wear of tribocoupled parts and the production of excess entropy and its flow is determined. Expressions for the intensity of wear of tribocoupling parts were obtained, taking into account thermal processes in the friction zone. The trends of changes in the characteristics and properties of tribocouplers of components, systems and machine aggregates with a change in entropy have been clarified.

Key words: entropy approach, tribocoupling of parts, self-organization, friction zone, property.

Introduction

The leading role in synergetics is attributed to the entropy approach [1,2], which consists in the fact that the internal activity of tribocouples of parts, nodes, systems, and machine assemblies is opposed to the disordering element of entropy. Under certain conditions, this leads to the orientation of self-organization of processes and states in them.

At the same time, the processes and states of the materials of the parts must be irreversible, and the tribocouplings of the parts is an open system and far from the state of thermodynamic equilibrium. It is characteristic that entropy, which is produced in tribocouplings of parts, does not accumulate in them, but is brought out. There is a flow of negentropy from the external environment. In non-equilibrium tribocouplings of parts, fluctuations are accumulated and amplified and obey the principle of positive feedback.

As a result of increased fluctuations, the tribocouplings of the materials of the parts becomes more unstable, the previous order and structure are destroyed and qualitatively new ones arise when energy is dissipated in the external environment.

The process of self-organization begins at the micro level in the local areas of the friction zone of the materials of the parts and is accompanied by an increase in fluctuations under the influence of external influences.

The emergence of a new order in tribocoupled materials occurs spontaneously at the moment of extreme instability, when the materials of the parts acquire significant coherence. Irreversibility, instability and imbalance are the most fundamental properties of tribocouples of components, systems and machine assemblies than stability and equilibrium.

The characteristics and properties of materials of tribocouplers of parts have a probabilistic nature and randomness has a significant impact on their further development.

The development of tribo couplings of parts in operation is a non-linear process, and therefore can be described by a non-linear differential equation.

According to the theory of non-equilibrium processes [1-4], the properties of tribocouples of parts far from the equilibrium state become unstable and their return to the initial state is optional. At the same time, their behavior is ambiguous, but there are effects of coordination, correction of the behavior of its elements at macroscopic distances and time intervals [5]. Cooperatively coordinated behavior determines the processes of ordering, the emergence of certain structures from chaos, their transformation and complication [6]. The greater the deviations from equilibrium, the greater the coverage of correlations and interrelationships, the higher the coherence of processes characterized by nonlinearity and the presence of positive and negative feedback [6, 7], and the possibilities of controlling influence on the tribocoupling of node parts, systems and units of machines.

The effectiveness of the implementation of the entropy approach to the evaluation of the properties of the materials of the friction zones of the tribo-coupling parts of assemblies, systems, and machine assemblies increases when using the fundamentals of physical mesomechanics [8]. The study of regularities of the processes of friction and wear of the conjugations of parts and the development of new and improvement of known methods of theoretical evaluation of tribotechnical characteristics and properties is definitely relevant. In this regard, the introduction of the entropy approach to the assessment of tribotechnical characteristics and properties of the friction zone of the couplings of parts and the detection of their changes due to the change in entropy deserves attention.

Literature review

In the process of evolution, the external contribution to the total entropy of tribocoupling of parts can be arbitrary, depending on the parameters of the external environment and the nature of the interaction of parts. At the same time, two types of situations are possible:

– the total entropy decreases due to its return through the boundary surface of tribocoupling of parts:

$$dS/dt < 0\,; \tag{1}$$

– the total entropy is constant and maximal for the given conditions of operation of tribocouples of parts, but less than the entropy of their equilibrium state:

$$S_{\max} = \text{const} < S_{рівн.\max}\,. \tag{2}$$

If the flow of entropy is equal to its production, then the material of tribocoupling of parts is in a stable steady state or a state of current equilibrium. With a positive change in entropy, energy processes in tribocouplings of parts are always dissipative, that is, they are accompanied by a decrease and dissipation of energy. Dissipation of energy is the main feature of the current equilibrium, but, in accordance with the principle of self-integrity of equilibrium, the system cannot spontaneously leave it, and under external influence, the processes aimed at its compensation intensify. This is similar to the manifestation of the phenomena of electromagnetic induction [9]. According to the principle of minimum entropy production, the laws of nature [10] assume several options for the development process (organization), and the one that corresponds to the minimum dissipation of energy is realized. At the same time, the driving force behind the processes of self-organization of materials of tribocouplers of parts is phase transformations or their sequence, as a result of which there is a transition to a more ordered state corresponding to lower symmetry [11].

In such conditions, the processes of friction and wear are realized against the background of increased gradient ratios of temperature, stresses, chemical potential, concentration of alloying elements and defects in the crystal structure. A complex set of physico-mechanical, physico-chemical, tribological and rheological phenomena is observed. Since friction and wear are non-equilibrium thermodynamic processes, self-organizing changes in the tribocoupling of parts are inevitable and mandatory [1,2,12-14].

The internal manifestation of self-organization in the materials of tribocouplers of parts is:

– formation of secondary structures on the surfaces of parts with higher strength and wear resistance compared to the initial structures;

– the development of equilibrium roughness, regardless of the initial microgeometry of friction surfaces;

– increasing the actual contact area due to the working wear and, as a result, reduction of contact loads;

– implementation of the effect of selective transfer, etc. [15-17].

The external manifestation of the self-organization of materials in the tribocoupling of parts is: reduction and stabilization of energy, power and tribotechnical characteristics, in particular, the coefficient of friction, temperature, moment of friction, intensity of wear. At the same time, it is advisable to analyze the general patterns of self-organization from the standpoint of a system-oriented approach, dividing the materials of parts and the working (technological) environment into subsystems of local areas of contact interaction, which are united by mode, structural, geometric and other signs of affinity. Local areas, in turn, consist of subsystems – ensembles [18-20], within which microstructural processes are implemented, including internal mass transfer [18-20].

Purpose

The purpose of this work is to use the entropy approach to theoretically substantiate the realization of the state of self-organization of tribocoupling materials of components, systems and assemblies of machines and to identify the direction of the properties and characteristics of the materials of the friction zones from the change in entropy.

Results

On the friction surfaces and in the surface layers of the materials of tribocoupled parts, a whole set of various processes takes place at the same time, due to which the tribocoupled parts lose their thermodynamic stability. Some of them are directly caused by friction, and others are indirectly related to it.

The first group of physical processes includes heat removal, mass transfer from the friction zone, deformation of the surface layers of parts, etc. They are caused, as a rule, by gradients of temperature, chemical potential, stress, concentration of defects, etc., which arose as a result of friction and preliminary strengthening or modifying processing of the materials of the parts.

The second group of processes, according to the equilibrium diagrams of the state of materials of the parts, takes place at the temperature of heating of the surface layers from the work of frictional forces. Basically, these are phase transitions and chemical reactions. At the same time, heating conditions the kinetic possibility of relaxation processes, the driving forces of which are not related to friction and do not depend on it, but exist both in the friction zone and in the adjacent layers and are directed chaotically. It is also necessary to highlight the processes that occur in the friction zone, but are caused not by friction, but by operating conditions. Examples of such processes are processes in the tribocoupling of parts observed during friction with vibration, irradiation, and other influences [22, 23].

The excess production of entropy during the realization of the self-organization effect must be negative and agree with Lyapunov's theorem [1, 24]:

$$\frac{1}{2}\frac{\partial}{\partial t}\left(\delta^2 S\right)=\sum_n \delta X_n \delta J_n\,, \tag{3}$$

where X_n and J_n – thermodynamic forces and thermodynamic flows, respectively.

If $\sum_n \delta X_n \delta J_n \le 0$, then the materials of tribocouples of parts lose stability and self-organization with the formation of dissipative structures can be observed. If friction processes are significant , we have:

$$\frac{dS}{dt}=\frac{(f_{тр}(v,t)Nv)^2}{\lambda_м(v,t)S_{тр}T^2}\,, \tag{4}$$

where $f_{тр}(v,t)$, $S_{тр}$ – coefficient and surface area of friction; N – load; v – relative speed of parts; $\lambda_м(v,t)$, T – the coefficient of thermal conductivity and the temperature in the friction zone. If the speed of movement is variable, and $\lambda_м = \mathrm{const}$, then the excess production of entropy is:

$$\frac{\partial}{2\partial t}\left(\delta^2 S\right)=\frac{N^2}{T^2 S_{тр}\lambda_м}\left(\frac{\partial f_{тр}}{\partial v}+f_{тр}\right)^2(\delta v)^2. \tag{5}$$

If $\lambda_м \ne \mathrm{const}$ and $v \ne \mathrm{const}$, then we have:

$$\frac{\partial}{2\partial t}\left(\delta^2 S\right)=\frac{N^2}{T^2 S_{тр}\lambda_м}\left(\frac{\partial f_{тр}(v,t)}{\partial v}v+f_{тр}(v,t)\right)\left(f_{тр}(v,t)+v\frac{\partial f_{тр}(v,t)}{\partial v}-\frac{f_{тр}(v,t)v}{\lambda_м}\frac{\partial \lambda_м(v,t)}{\partial v}\right)(\delta v)^2. \tag{6}$$

Analysis of equation (6) shows that when its positive right-hand side tribocoupling of parts does not lose stability, and when it is negative, it does. With negative entropy production, we get the following conditions:

$$\partial f_{тр}(v,t)/\partial v \ge 0, \qquad \partial \lambda_м(v,t)/\partial v \ge 0; \tag{7}$$

$$\partial f_{тр}(v,t)/\partial v \le 0, \qquad \partial \lambda_м(v,t)/\partial v \le 0. \tag{8}$$

Note that conditions (7) and (8) are sufficient for the realization of self-organization in the tribocoupling of parts, in the presence of synergistic interaction of two or more processes in the friction zone. At the same time, the material of the tribocoupling parts is complicated, new structures appear in the surface layer of the material and in the adjacent layers of the working (technological) environment.

From the point of view of entropy production, the self-organization of the tribocoupling materials of parts can create such conditions when the absolute value of the negative entropy associated with friction increases, but the overall entropy production does not change [1, 2, 24]. This indicates that the tribocoupling of parts from the outside can receive high-power energy without a significant change in the intensity of wear, and a significant part of the work of friction forces will be spent on unbalanced processes. The analysis of the self-organization of the materials of the tribocoupled parts and the working (technological) environment within the limits of nonlinear thermodynamics [24-26] confirms that with strong excitation of the equilibrium tribocoupled parts, their behavior becomes diverse and non-linear. In this regard, a more active and effective way of improving the tribocoupling of parts is the combination of the Schrödinger approach and nonlinear thermodynamics [25, 26], and the powerful and targeted excitation of the tribocoupling materials can be implemented by highly ordered energy flows (laser radiation [1]) or substances that ensure their transition to a more organized and stable state.

The above makes it possible to formulate the main provisions of the entropy approach to changes in the properties of the friction zones of tribocoupling parts of assemblies, systems and machine assemblies:

1. Tribocoupling of machine parts is an open thermodynamic system that exchanges energy and mass between their elements and the environment. The entropy balance equation is used to describe their behavior:

$$\frac{d}{dt}\int_V s dV = \int_V (\sigma_s - divJ_s) dV \, , \tag{9}$$

where σ_s , J_s – production and flow of entropy density, respectively; s is the volume density of entropy.

2. Friction is a process accompanied by fluctuations of fields, speed, pressure, and temperature, which are not destroyed during the evolution of the state of tribocouples of parts and the development of their parameters over time. When they fade, there is a transition to thermodynamic states with minimal entropy production, which are bifurcation points with an optimal mode of operation, from the point of view of wear and manifestation of the synergistic principle of self-organization.

3. In thermodynamics of open systems, including and in the tribocoupling of parts, the driving forces of the processes are gradients of temperature, concentration, chemical and electrical potentials, which determine various processes of transfer of heat flows, matter (diffusion and chemical reaction) and electrical charges.

The use of the entropy criterion of destruction and the equation of the entropy balance shows that the process of wear of the materials of the tribocoupling parts with a volume of V is not responsible for the entire density of entropy accumulated by it, but a part of it, that is, the coefficient k_S – the entropy utilization coefficient.

In this case, the entropy balance equation has the form:

$$\frac{d}{dt}\int s dV = k_s \left(\int_V (\sigma_s - divJ_s) dV \right). \tag{10}$$

It should be noted that the entropy criterion of destruction acts as a measure of the workability of the material of tribocoupler parts. At the same time, the effects of thermal, mechanical, chemical, electrical and convective processes on the production and formation of the entropy flow are taken into account. The entropy density accumulated by the material of the parts, in its physical essence, characterizes its wear resistance.

To evaluate the tribotechnical characteristics, the dynamic development of the processes in the materials of the tribocouplers of the parts, due to various mechano-physical and chemical-physical reasons, should be considered. This is taken into account primarily in the production of excess thermal entropy on the spots of actual contact of the tribocoupler parts.

After integrating equation (10) over the investigated time interval (0,t), we have:

$$\int_V \frac{sdV}{dt} = k_s \int_0^{V_u} \left(\sigma_s - divJ_s \right) dV \, . \tag{11}$$

At the same time, the rate of volume wear of the material is equal to:

$$\frac{dV_u}{dt} = \frac{k_s \int_V \left(\sigma_s - divJ_s \right) dV}{s} \, . \tag{12}$$

Considering the contact area S_k, we have:

$$\frac{dV_u}{dt}=\frac{k_s\int_0^{V_u}(\sigma_s-divJ_s)S_k dV}{s}. \tag{13}$$

At the nominal contact area S_{nk}, the volumetric wear rate is equal to:

$$\frac{dV_u}{dt}=\frac{k_s S_{nk}\int_0^{u}(\sigma_s-divJ_s)dx}{S_r}, \tag{14}$$

where S_r is the limiting entropy density of the part material.
By definition, the intensity of wear of tribocoupling parts is equal to:

$$I_{1u}=\frac{dV_{1u}}{dt}\frac{1}{S_{1k}v_{mp}};\ I_{21u}=\frac{dV_{2u}}{dt}\frac{1}{S_{2k}v_{mp}}, \tag{15}$$

where v_{mp} – the relative speed of movement of the part.
Considering (14) in expressions (15), we have:

$$I_{1u}=\frac{k_s\int_0^{u1}(\sigma_s-divJ_s)dx}{v_1\cdot S_{u1}};\ I_{1u}=\frac{k_s\int_0^{u2}(\sigma_s-divJ_s)dx}{v_2\cdot S_{u2}}. \tag{16}$$

Considering the significant contribution to friction and wear of thermal processes, it can be assumed that $k_s=\frac{T_{cn}}{T}$, where T_{cn} – the flash point, T – the temperature of the working surface of the part. At the same time, the entropy density in the worn material of the parts has two components: the standard (zero) value and the addition from the influence of thermal effects:

$$s_u=s_0+\int_{T_0}^{T}\frac{C_p}{T}dT, \tag{17}$$

where C_p – the heat capacity of the surface layer of the part material.

If the components of thermal processes, including oxidizing ones, are taken into account, then the cumulative production of entropy of the materials of tribocoupler parts is added to the expression in brackets of expressions (16):

$$\sigma_T=\sum_{i=1}^{k}G_{Ti}\frac{du_i}{dt}\eta_{Ti}\frac{1}{T}=\sum_{i=1}^{k}(H_{Ti}-TS_{Ti})\frac{du_{Ti}}{dt}\eta_{Ti}\frac{1}{T}, \tag{18}$$

where G_{Ti}, H_{Ti} and S_{Ti} – the Gibbs potential, enthalpy and entropy, i – a component of thermal processes; the formation of the i -th grade oxide; $\frac{du_{Ti}}{dt}$ – wear rate.

Taking into account the predominant role of thermal processes in material wear and dependence (18), we finally have:

$$I_u=\frac{\int_0^{u}\lambda_T\left[\left(\frac{dT}{dx}\cdot\frac{1}{T}\right)^2-\frac{d^2T}{dx^2}\cdot\frac{1}{T}\right]dx+\sum_{i=1}^{k}\left[(H_{Ti}-TS_{Ti})\frac{du_{Ti}}{dt}\eta_{Ti}\cdot\frac{1}{T}\right]\cdot\frac{T_{cn}}{T}}{Vs_u}. \tag{19}$$

From the last dependence, it follows that to reduce the intensity of wear, it is necessary to reduce the contact temperature T in various ways, including the use of triborecovery technologies to form coatings of the optimal composition, reducing the parameter k_s, increasing the entropy of the material of the part s_u and the entropy of the component thermal processes S_{Ti}.

In thermodynamics and statistical physics, entropy is a function of the state of the system. It is included in the mathematical expression of the second principle of thermodynamics:

$$TdS = dU + dA, \tag{20}$$

where T – the thermodynamic temperature, dU – the change in internal energy; dA – a change in the work of internal forces. If a certain amount of heat is introduced into the thermodynamic system (tribocoupling of parts) dQ, then the entropy change dS in the reverse process is equal to $dS = dQ/T$. Note that thermal entropy, in contrast to configurational entropy, is related to processes in the crystal lattice of the material of the tribocoupler parts.

Due to the fact that the tribocoupling of parts functions under conditions of intense heat generation, depending on the assessment of the intensity of wear and tear, I_u value s_u has the content of specific thermal entropy. Entropy – the most important thermodynamic characteristic of the material of the elements of tribocoupling of parts, which determines the speed and direction of the chemical reaction, the magnitude of the Gibbs and Helmholtz potentials, etc.

The theoretical justification of the experimental results revealed a number of generalized patterns of change in the entropy of materials of tribocoupling of parts:

– the complication of the composition of the materials of parts leads to an increase in its entropy;

– the harder the material of the part, the lower the entropy;

- the value of the standard specific entropy of an element s_0 depends on its serial number z in the. table. D.I Mendeleev and changes in a certain direction, having a minimum point;

– in the amorphous state, the materials of the surface state of parts have an entropy greater than in the crystalline state;

– entropy is sensitive to the degree of dispersion of the material: as the grain size decreases, entropy increases;

– the greater the density of the substance, the material of the part, the lower its entropy, there is an inverse linear relationship between these values: $\rho_м \sim 1/s$.

Existing materials for tribocoupling parts are mainly multi-component materials with a heterogeneous structure, which mainly consist of two phases: hard alloys – carbides and metal bond, alloyed cementite, martensite and residual austenite. The components of materials differ in mechanical and physicochemical characteristics and properties. It is known from the thermodynamics of non-equilibrium processes that for multicomponent systems, if they are considered as ideal solid solutions, all thermodynamic potentials – Gibbs, Helmholtz, enthalpy and entropy - have the property of additivity. It follows that the entropy density of a hard alloy can be calculated as the sum of products of the molar fraction of each component by the value of its standard entropy density:

$$s_{ij} = \eta_1 s_i + \eta_2 s_j, \tag{21}$$

where $\eta_1 + \eta_2 = 1$, η_1 and η_2 – the corresponding molar fraction of the component, and s_i, s_j – the entropy density of each component.

One of the methods of managing performance indicators of tribocoupler parts made of hard alloy is to improve the structure of the material in the broadest sense of the word. The effect is also taken into account that with the reduction of the size of the initial components of the alloy to the nanolevel, as well as the optimization of the phase components of the carbide and binder phases, the entropy of the material of the parts decreases, and the wear resistance increases.

This determines the implementation of the improvement of the structure and composition of materials of tribocoupler parts and the reduction of their entropy in the following ways:

– change in the composition of the carbide phase;

– development of new hard alloys;

– change in the composition of the binding phase;

– reducing the size of the carbide phase from 2.0...2.5 μm to nanosize, ensuring an increase in the density, strength of the alloy and the corresponding wear resistance of the parts and their tribocoupling as a whole.

Conclusions

1. The implementation of the self-organization effect associated with excess entropy production is theoretically substantiated.

2. The relationship between the tribotechnical characteristics of the friction zone and the rate of change of entropy in the tribocouplings of parts was obtained.
3. With the negative production of the entropy of tribocoupling of parts, the conditions for realizing self-organization are obtained.
4. The main provisions of the entropy approach to changes in the properties of the friction zones of parts of tribocouplings of assemblies, systems and machine assemblies are formulated.
5. Derived expressions for estimating the intensity of wear of tribocoupling parts. They were refined taking into account the predominant role of thermal processes in the wear of parts materials.
6. Based on the experimental results, the directions of changes in the characteristics and properties of materials of tribocoupling parts from the change in entropy based on the entropy approach are substantiated.

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Аулін В.В., Тихий А.А., Кузик О.В., Лисенко С.В., Гриньків А.В., Жилова І.В. Виявлення змін характеристик і властивостей зон тертя деталей трибоспряжень систем і агрегатів машин на основі ентропійного підходу

З'ясовано роль ентропії в процесах тертя і зношування матеріалів трибоспряження рухомих деталей. Теоретично обґрунтовано реалізацію ефекту самоорганізації матеріалів в залежності від виробництва ентропії. Отримано умови самоорганізації при від'ємному виробництві ентропії. Визначено зв'язок швидкості об'ємного зношування трибоспряження деталей від виробництва надлишкової ентропії і її потоку. Отримано вирази для інтенсивності зношування деталей трибоспряження з урахуванням теплових процесів в зоні тертя. З'ясовано тенденції зміни характеристик і властивостей трибоспряжень деталей вузлів, систем і агрегатів машин зі зміною ентропії

Keywords: ентропійний підхід, трибоспряження деталей, самоорганізація, зона тертя, властивість.