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IRREVERSIBILITY OF FRICTION AND WEAR PROCESSES

NIEODWRACALNOŚĆ PROCESÓW TARCIA I ZUŻYWANIA

Key words:	thermodynamic system, friction, wear, energy dissipation, dissipation work, friction heat.
Abstract:	Ways of energy dissipation by friction are analysed from a thermodynamic perspective. The non-equilibrium and irreversibility of processes in tribological systems are found to be sufficient conditions for energy dissipation. M. Planck's currently prevailing opinion that mechanical work can be converted into heat without limitations, e.g., by means of heat, is demonstrated not to apply to the friction of solids subject to wear. Ranges of work conversion into friction heat are determined. The generation of tribological wear particles is dependent on work of mechanical dissipation and its components – surface and volume work. A friction pair or its fragments, where energy is directly dissipated, are treated as open thermodynamic systems. The processes in place are described with the first law of thermodynamics equation. The effect of friction heat and the work of mechanical dissipation on variations of internal energy, enthalpy, and energy transferred to the environment as heat are defined. These dependences should be addressed when planning and interpreting tribological tests.
Słowa kluczowe:	system termodynamiczny, tarcie, zużywanie, rozpraszanie energii, praca dyssypacji, ciepło tarcia.
Streszczenie:	W artykule zanalizowano sposoby rozpraszania energii przez tarcie z punktu widzenia termodynamiki. Stwierdzono, że nierównowaga i nieodwracalność procesów zachodzących w układach tribologicznych jest warunkiem wystarczającym do wystąpienia rozpraszania energii. Wykazano, że obwiązująca współcześnie opinia M. Plancka, że pracę mechaniczną można zamienić na ciepło bez ograniczeń, np. przez tarcie, nie dotyczy przypadków tarcia ciał stałych podlegających zużywaniu. Ustalono zakresy zamiany pracy na ciepło tarcia. Powstawanie cząstek zużycia tribologicznego uzależniono od pracy dyssypacji mechanicznej i jej elementów składowych – pracy powierzchniowej i objętościowej. Para cierna lub jej fragment, w którym rozpraszanie energii następuje bezpośrednio, potraktowano jako otwarty system termodynamiczny. Zachodzące procesy opisane zostały równaniem pierwszej zasady termodynamiki. Określono wpływ ciepła tarcia i pracy mechanicznej dyssypacji na zmiany energii wewnętrznej, entalpii i energii przekazywanej do otoczenia na sposób ciepła. Te zależności należy wziąć pod uwagę przy planowaniu testów tribologicznych i ich interpretowaniu.

INTRODUCTION

The discussion in this paper serves the purpose of a more in-depth understanding of friction and assistance with tribological experimentation. Without this understanding, like M. Grebe **[L. 1]** rightly notes, effective laboratory testing of friction and wear and correct interpretation of results, and in particular their transfer to real engineering objects, are impossible. Fundamental thermodynamic concepts of importance to tribology are the starting point for the discussion.

The lack of equilibrium in a tribological system and the irreversibility of processes play important roles as they are directly related to energy dissipation. J.P. Joule (1843) determined friction heat as a quantity of friction work in water contained in a calorimeter. This type of dissipating effect plays the key role in the energy balance that characterises real technical processes. Part 2 of this study explains the thermal nature of mechanical energy dissipation. Section 3 concerns another mechanism of energy degradation, namely, the work of dissipation as a typical mechanical effect. The work of dissipation

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causes the disintegration of materials in friction. The presence of these mechanisms of energy dissipation also requires a comprehensive approach in order to determine appropriate analytical dependences to set boundaries to energetic impacts of the mechanisms. Part 4 offers recommendations for the application of thermodynamics to tribological testing.

NON-EQUILIBRIUM, IRREVERSIBLE PROCESSES, AND FRICTION HEAT

Phenomenological thermodynamics studies the thermodynamic system, which is defined as part of material space delimited with a material or abstract surface. Space outside the system is known as the environment. A system exchanging mass and energy with its environment is open and one exchanging only energy is a closed system. Based on this definition, a friction pair or its part can be treated as a thermodynamic system. If mass variation caused by friction is taken into account, such a system should be considered open. Transformations analysed with methods of classic phenomenological thermodynamics form a continuum across successive states of equilibrium from a starting to an end point. Such transformations are referred to as quasi-static. They are very slow, so that thermodynamic equilibrium is maintained at all times. According to B. Staniszewski [L. 2], a quasi-static model of transformations perfectly fits most real processes. A quasi-static transformation of a system from an initial to a final state is known as reversible if the system can be restored from its final to its initial state without causing changes to the environment. A transformation is said to be irreversible where a system passes from an original to a final state, then from the final to the initial condition, and this is associated with changes to the environment. Consideration of the reversibility of thermodynamic processes has led to the conclusion that quasi-static transformations are largely reversible. In addition, an infinitely small modification to parameters is sufficient to reverse their direction. For instance, heat flow from an environment at temperature $\Theta + d\Theta$ to a system of temperature Θ is a quasi-static process, because an infinitely small change of ambient temperature, $2d\Theta$, is enough to revert the process direction. Not every infinitely small and slow process is quasi-static. K. Zalewski [L. 3] describes the irreversibility of the friction process in a very simple manner. If a force $(1 + \varepsilon) T$, where $\varepsilon > 0$, is needed to move chalk in a specific direction along a table, then after an external parameter is subject to an infinitely small change by 2ε, so that force $(1-\varepsilon) T$ acts on the chalk, the motion is no more. Therefore, a substantially larger, finite change of force applied, $(-1-\varepsilon) T$, is necessary to change the direction of chalk motion.

Process irreversibility can be expressed with the equation for the first law of thermodynamics for closed systems including heat of friction. The rise of the system's internal energy ΔU is a sum total of work A_{1-2}, heat Q_{1-2}, and dissipated heat Q_{diss}:

$$\Delta U = A_{1-2} + Q_{1-2} + Q_{diss}. \qquad (1)$$

The index 1-2 represents the transition of the system from state 1 to 2. The positive signs on the right-hand side of (1) mean that their increase causes growth of internal energy. Two types of heat are given in (1). The first, Q_{1-2}, comes from the environment. It may be both positive and negative. The other, Q_{diss}, stems from dissipation of mechanical energy (or another, usable energy, e.g., electric) and can only be positive. Both types of heat affect parameters of a medium in the system in the same way. They are added, therefore, to form the notion of total heat Q_{c1-2}:

$$Q_{c1-2} = Q_{1-2} + Q_{diss}. \qquad (2)$$

The presence of dissipation heat in the system is proof of the irreversibility of the entire transformation, that is, of energy loss. Such phenomena are the subject for the thermodynamics of non-equilibrium processes. Quasi-static transformations are considered in practice, but parameter variations caused by irreversibility of a process (losses) are addressed by incorporating appropriate quantities, e.g., friction heat, in the system. The generation mechanism of the heat is not explored, it is only introduced on the basis of appropriate experimental data, and the description of a real phenomenon is supplemented in this way [L. 4]. This implies that properly modified classic thermodynamics can replace thermodynamics of non-equilibrium processes to a limited extent. This limitation basically consists in the omission of analysis of the "coupled processes." Heat Q_{diss}, originally described by R. Clausius as uncompensated heat, is a measure of process irreversibility. It depends not only on an initial and final state, but also on a path of transformation. R. Clausius introduced the function of entropy S, another measure of process irreversibility. This magnitude is defined as a total differential, dS, in the following manner [L. 2]:

$$dS = \frac{\delta Q_c}{\Theta}, \qquad (3)$$

where δQ_c – elementary increment of total heat, δ represents one-form, Θ – absolute temperature. In an adiabatic process, where $Q_{1-2} = 0$,

$$dS = \frac{\delta Q_{diss}}{\Theta}. \qquad (4)$$

If $Q_{diss} > 0$, i.e. in the case of an irreversible adiabatic process, the second law of thermodynamics can be formulated as follows:

$$dS > 0. \qquad (5)$$

If a quantity of heat δQ is supplied from a solid "1" at temperature Θ_1 to solid "2" at Θ_2, with no other irreversible transformation taking place, the entropy of "2" would rise by $\delta Q/\Theta_2$ and entropy of "1" would reduce by $\delta Q/\Theta_1$. Thus, the entire entropy undergoes the following change:

$$dS = \delta Q \; \frac{\Theta_1 - \Theta_2}{\Theta_1 \Theta_2} \; . \qquad (6)$$

This dependence allows for an original interpretation of work conversion into heat by way of friction or impact [L. 5]. If $\Theta_2 = \Theta$ is assumed in (6) where $\Theta_1 = \infty$, then $dS = \delta Q/\Theta$, hence work of friction $\delta A = \delta Q$ behaves like δQ heat of an infinitely high temperature. Therefore, friction heat is always positive, that is, it always increases internal energy of a system. M. Planck believed mechanical work can be converted into heat without limitations, e.g., via friction, yet a complete conversion of heat into work is impossible. His view is universally accepted today. Thermal efficiency η_c is maximal in the Carnot cycle:

$$\eta_c = 1 - \frac{\Theta_2}{\Theta_1}, \qquad (7)$$

where Θ_1 – temperature of heat source, Θ_2 – temperature of cooler.

The Carnot cycle consists of two isotherms and two adiabatics. A clockwise cycle for a heat engine is considered. After the stages of the process are reversed, an anticlockwise cycle for a heat pump takes place. In a tribological process, it is important to what degree friction work can be converted into heat.

If the mechanical effect with regard to the Carnot principle is substituted with the thermal effect, and the notion of absolute temperature with absolute pressure, then the Carnot principle is generalized to Afanasyeva-Ehrenfest cycle [L. 6]. This cycle consists of two isobars (p_1, p_2) and two isochors (V_1, V_2) that characterize the gas medium in a cylinder closed with a piston. These thermodynamically symmetrical cycles are analysed in detail by M. Mieczyński [L. 7]. Their graphic representations are shown in Figures 1 and 2. Efficiency of Afanasyeva-Ehrenfest cycle – η_{A-E} is a relationship of the cycle heat Q_z to work A of the medium in circulation, executed for its benefit by the environment:

$$\eta_{A-E} = \frac{Q_z}{A} = \frac{\oint \delta Q}{\int_{lp2} p_1 dV}, \qquad (8)$$

where the change of volume $dV = Fds$, ds – elementary piston displacement, F – piston surface.

The cycle heat is expressed according to the first law of thermodynamics as follows:

$$Q_z = \oint \delta Q = \oint \delta A, \qquad (9)$$

whereas

$$\oint \delta A = \int_{lp2} p_1 dV + \int_{lp2} p_2 dV = p_1(V_2 - V_1) + p_2(V_4 - V_3), \qquad (10)$$

since $V_2 - V_1 = V_4 - V_3$, the efficiency η_{A-E} is Expressed by [L. 7]:

$$\eta_{A-E} = \frac{(p_1 - p_2)(V_2 - V_1)}{p_1(V_2 - V_1)} = 1 - \frac{p_2}{p_1} \; . \qquad (11)$$
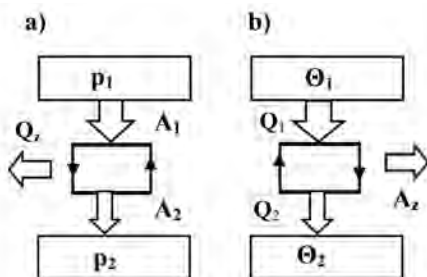

Fig. 1. Thermodynamic circuit diagrams as per: a) Afanasyeva-Ehrenfest, b) Carnot [L. 7]
Rys. 1. Schematy obiegów termodynamicznych według: a) Afanasjewej-Ehrenfest, b) Carnota [L. 7]
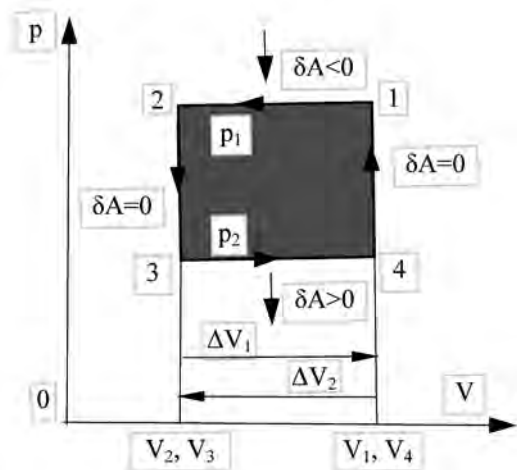

Fig. 2. Afanasyeva-Ehrenfest cycle in the system of coordinates p-V [L. 7]
Rys. 2. Cykl Afanasjewej-Ehrenfest w układzie współrzędnych p-V [L. 7]

It can be stated, therefore, that work cannot be fully converted into heat, just like heat cannot be fully converted into mechanical work. Theoretical analysis shows, in addition, that the efficiency of a real cycle η is always less than η_{A-E}.

The foregoing discussion has not addressed mass exchange between the system and the environment. The thermodynamic parameter known as enthalpy $I = i \cdot m$ is introduced to the description of the energy balance in open systems, with i – average specific enthalpy of a substance exchanged with the environment, and m – mass of the same substance. The equation for the first law of thermodynamics in this case becomes [L. 2]:

$$\Delta U = \Delta I + Q_{1-2} + A_{t1-2}, \qquad (12)$$

where A_{t1-2} – technical work.

Enthalpy I, as an extensive thermodynamic parameter, is defined as follows with reference to a gas medium:

$$I = U + pV. \qquad (13)$$

Technical work characterising open systems is decided by the following dependence in the case of reversible processes:

$$A_{t1-2} = A_{1-2} + (p_2V_2 - p_1V_1). \qquad (14)$$

If friction is present in a system, part of technical work A_{t1-2} is reversible – A_{tod} and the rest remains as friction heat Q_{diss}, i.e.:

$$A_{t1-2} = A_{tod} + Q_{diss}. \qquad (15)$$

(12) can be modified by introducing total heat, namely:

$$\Delta U = \Delta I + Q_{c1-2} + A_{tod}. \qquad (16)$$

(1) and (16) describe all changes, including friction, in thermodynamic systems. If only friction occurs in a system, reversible work must be removed from the equation for the first law of thermodynamics. The thermodynamic description of friction then has the following form:

– For closed systems:

$$\Delta U = Q_{c1-2}, \qquad (17)$$

– For open systems:

$$\Delta U = \Delta I + Q_{c1-2}. \qquad (18)$$

The above dependences describe processes in real thermodynamic systems, including friction losses. The discussion ignores tribological wear as the work of friction forces is equalized with friction heat ($A_{1-2} = Q_{dyss}$ or $A_{t1-2} = Q_{dyss}$). This limitation also arises from the assumption that a system is filled with a substance free from defects and the impact of surface energy, that is, a simple solid. Analysis of wear must resign from the simple solid model and the role of surface tension in generation of wear products and thermodynamic non-equilibrium in a tribological system must be taken into account. An analytical description of tribological wear can be based on the equation for the first law (12) if interpretations of enthalpy increment ΔI and technical work A_{t1-2} address characteristics of tribological processes.

WORK OF MECHANICAL DISSIPATION

Original material structure must be modified to separate wear particles from a top layer. This involves the emergence and development of point, linear, and superficial defects. A new area is produced then – a boundary between two phases. Atoms and particles of a solid on its surface have a greater energy than the energy they would have inside the solid. This is the potential surface energy of an atom or particle, defined as specific surface energy or surface energy for short. In order to produce this excess energy, atoms or particles must be carried mechanically from inside a solid on to its surface. The first law of thermodynamics regarding substance transformation in the surface phase can be expressed as [L. 8]:

$$dU_F = \delta Q_F + \delta A_F = \delta Q_F + e_F dF, \qquad (19)$$

where the F bottom index refers to the surface produced while δQ_F is the elementary heat increment and δA_F elementary work to produce a new surface at the time of transformation; e_F – specific surface energy.

For multi-component systems featuring surface phenomena, the increment of the system's internal energy is described with [L. 9]:

$$dU_F = \Theta dS - pdV + e_F dF + \sum_{i=1}^{k} \mu_i \, dm_i, \qquad (20)$$

where μ_i – chemical potentials of components with masses m_i, dS – entropy growth at temperature Θ.

The surface expands and geometrical properties of a system change when energy is supplied as mechanical work δA_{dyss}. This can be formulated as follows:

$$\delta A_{dyss} = \delta A_V + \delta A_F, \qquad (21)$$

where $\delta A_V = pdV$, $\delta A_F = e_F dF$.

Nominal surface of solid contact A_n is distinguished by tribology, bounded by its nominal dimensions where nominal unit pressures apply p. In addition, there is real contact surface A_r defined as the sum total of elementary contacts between irregularities A_{ri} with the area of nominal surface A_n. Momentary unit pressures prevail on the real surface, normally identified with hardness H of the softer material of one of the solids. Therefore, solid systems in non-equilibrium with regard to pressure must be addressed by the analysis of tribological processes.
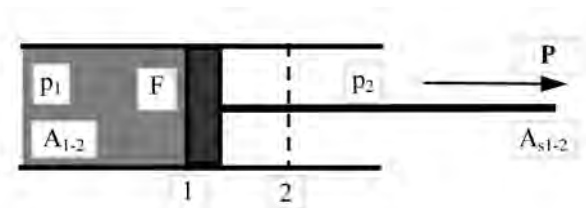
Fig. 3. **Graphic representation of work of thermodynamic processes A1-2 and work performed by the system As1-2 [L. 7]**
Rys. 3. Graficzne przedstawienie pracy procesów termodynamicznych A_{1-2} oraz pracy wykonywanej przez system A_{s1-2} **[L. 7]**

A system of solids in non-equilibrium with regard to pressure is shown in **Fig. 3**. The mechanical efficiency of the system of solids constituting power P is determined by considering the fact each solid realizes a thermodynamic process of its own and respective work. Pressure p_1 is present in the cylinder to the left of the piston with surface F. Pressure $p_2 < p_1$ prevails to the right of the piston. After the piston is shifted from position 1 to 2, gas with pressure p_1 has executed work A_{1-2}. Work A_{s1-2} of the system is expressed with the following:

$$A_{s1-2} = \int_{1-2}(p_1 - p_2)dV = \int_{1-2}\frac{(p_1 - p_2)}{p_1}(p_1 dV).$$

(22)

However, absolute work A_{1-2} at pressure p_1 is an integral:

$$A_{1-2} = \int_{1-2} p_1 dV .$$

(23)

The degree to which the absolute work is utilised is efficiency η_s of a system of interacting solids, namely:

$$\eta_s = \frac{A_{s1-2}}{A_{1-2}} = \frac{\int_{1-2}(p_1 - p_2)dV}{\int_{1-2} p_1 dV} = 1 - \frac{\int_{1-2} p_2 dV}{\int_{1-2} p_1 dV}.$$

(24)

If the pressures p_1 and p_2 do not change between the states 1 and 2, then

$$\eta_s = \frac{p_1 - p_2}{p_1};$$

(25)

thus, the efficiency of absolute work of expansion in a non-equilibrium system at $p_2 > 0$ is always below one **[L. 7]**.

The development of a solid surface subject to wear caused by friction does not require further explanation, and the change of the volume dV is not as evident as in gas decompression. The mechanism of solid decompression in a friction zone can be presented on the basis of two physical laws: the law of mass conservation and the law of force quality on a real and nominal surface. Wear can be expressed by means of the mass flow of worn material. The law of mass conservations states a flux of mass $\dot{m}$ is the same on a real contact surface A_r as on a nominal contact surface of solids A_n. This results in different densities of mass fluxes. A material flow of initial density ρ can be observed on a real contact A_r; whereas, density on a nominal contact surface A_n, referred to as apparent, is substantially lower and equals ρ^* – **Fig. 4**. These densities are connected with volumetric wear and assigned to real V and apparent V^* volumes. This corresponds to a linear loss of solid dimensions – real h and apparent h^* – **Fig. 5**. The equation: $V^*\rho^* = V\rho$ is true to preserve the mass, while the condition of mass equilibrium means the equation $A_n p = A_r H$ is fulfilled, where H – hardness of the softer friction pair material, p – unit pressure on the nominal surface. The effect of wear is thus a function of volume V or V^* and
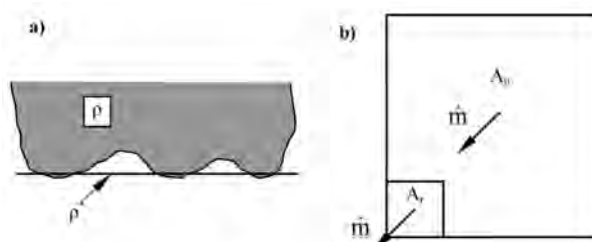
Fig. 4. **Diagram for analysis of the scale of wear: a) designation of real ρ and apparent ρ^* densities on the nominal surface A_n as wear particles are separated, b) designation of flow of wear product mass $\dot{m}$ across the nominal surface A_n and real contact surface A_r of the solid [L. 10]**
Rys. 4. Schemat do analizy charakteru wielkości zużycia: a) oznaczenie gęstości rzeczywistej ρ i gęstości pozornej ρ^* na powierzchni nominalnej A_n w momencie oddzielenia cząstek zużycia, b) oznaczenie przepływu masy produktów zużycia $\dot{m}$ na powierzchni nominalnej A_n i rzeczywistej powierzchni styku A_r ciała stałego **[L. 10]**
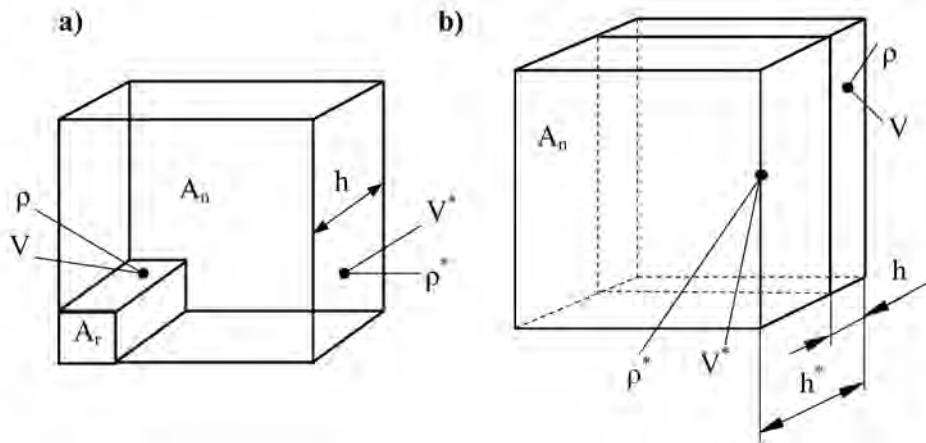
Fig. 5. **Determination of volume V of worn material on the nominal surface A_n with linear wear h, on the real surface A_r and with apparent linear wear h^* and apparent volume of wear V^* on the nominal contact surface A_n: a) variant $V = hA_r$, $V^* = hA_n$, b) variant $V = hA_n$, $V^* = h^*A_n$ [L. 10, 11]**

Rys. 5. Wyznaczenie objętości V startego materiału na nominalnej powierzchni A_n przez zużycie liniowe h, na powierzchni rzeczywistej A_r oraz przez pozorne zużycie liniowe h^* i pozorną objętość zużycia V^* na nominalnej powierzchni styku A_n: a) wariant $V = hA_r$, $V^* = hA_n$, b) wariant $V = hA_n$, $V^* = h^*A_n$ **[L. 10, 11]**

can be described with its increment ΔV. In parallel, the growth $\Delta h = h^*-h$ is assumed as the measure of linear wear. As the new definition of wear is introduced, no difference is found between the mass of worn material and the mass of wear products. Therefore, mass waste in a unit of volume is taken into account. For this reason, the difference between the initial material density ρ and apparent density ρ^* of the material in the area of contact between solid irregularities is the measure of mass wear.

Work of mechanical dissipation consists of two components – volumetric and superficial – eq. (21). Analysis of **[L. 15]** implies volumetric work is by three orders of magnitude greater than superficial work. The work of disintegrating a solid can be represented in a system of coordinates of shear stress-volume – cf. **Fig. 6** and the dependence (26):

$$A_{dyssV} = \mu(H-p)\Delta V = \mu V \frac{(H-p)^2}{p} \qquad (26)$$

Obviously, if the equality $H = p$ applies, that is, the nominal and real surfaces are equal, then $A_{dyssV} = 0$. Real contact surface A_r is equal to the sum total of all individual microsurfaces A_{ri} and commonly is a 10^{-5} to 10^{-2} part of the nominal surface A_n. It is generally known that the ratio of nominal to real surface equals the ratio of unit surface pressures corresponding to hardness H and nominal surface pressure $p = N/A_n$, where N – normal force. The following equalities result:

$$\frac{A_n}{A_r} = \frac{H}{p} = n_o, \qquad (27)$$

Fig. 6. **Volumetric work A_{dyssV} as wear particles are generated in the system of coordinates shear stress – volume [L. 10]**

Rys. 6. Praca objętościowa A_{dyssV} podczas tworzenia się cząstek zużycia w układzie współrzędnych naprężenie ścinające – objętość **[L. 10]**
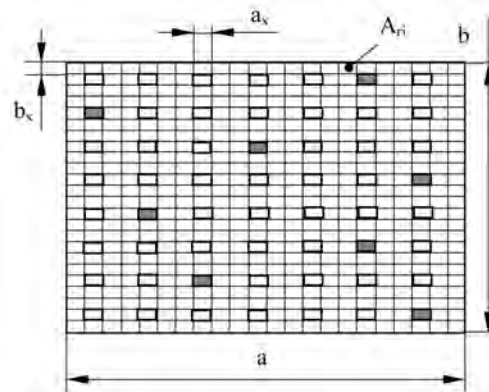
Fig. 7. **Nominal surface $A_n = a \cdot b$, divided into n_o^2 identical parts A_{ri}. The number of rectangles drawn with thick lines is n_o; number of rectangles drawn with thick lines and coloured is n_V [L. 12]**

Rys 7. Powierzchnia nominalna $A_n = a \cdot b$, podzielona na n_o^2 jednakowych części A_{ri}. Liczba prostokątów zaznaczonych grubymi liniami wynosi n_o; liczba prostokątów zaznaczonych grubymi liniami i zaciemnionych wynosi n_V **[L. 12]**

where n_o – number of real direct contacts between irregularities of the nominal surface, assuming each elementary contact surface is identical – **Fig. 7**. Assuming plastic material contact around elementary contacts, the nominal surface is n_o times greater than the real friction surface.

Wear coefficient k is introduced, which is the reciprocal of the number of repetitions n_k of elementary irregular contacts needed to produce a particle of wear:

$$k = \frac{1}{n_k} \ . \tag{28}$$

To illustrate the likelihood of wear particles separating from a solid in friction, the nominal surface A_n is divided into n_o^2 equal parts with elements of the surface A_{ri}. The fields, made with thick lines, are real contacts between surface irregularities. They number n_o. Some are coloured. These are locations where wear particles are produced and they number n_v. By the friction of equal length of side a, all elementary surfaces $A_{ri} = a_x b_x$ take part in wear, hence the dependence **[L.13]** is formulated as follows:

$$n_o^2 = n_V \frac{1}{k} = n_V n_k. \tag{29}$$

The probability of wear in any area of contact between surface irregularities is equal to the wear coefficient k:

$$\frac{n_V}{n_o^2} = k. \tag{30}$$

The probability of wear on an elementary surface of irregularities contact is equal to the ratio of **[L. 12]** and **[L. 13]**:

$$\eta = \frac{n_V}{n_o} = kn_o, \tag{31}$$

where η – efficiency of the particle generation process.

The efficiency of the particle generation process is minimum at $n_v = 1$, hence

$$\eta_{min} = \frac{1}{n_o} = \frac{p}{H} \ . \tag{32}$$

Evidently, the maximum efficiency of friction heating is the difference: 1-p/H, or

$$1 - \eta_{min} = 1 - \frac{p}{H} = \eta_{A\text{-}E}. \tag{33}$$

In the case of friction and wear of solids, friction heat is always lower than friction work.

If $n_v = n_o$-1 is substituted to (31), η becomes the greatest value, namely:

$$\eta_{max} = \frac{n_o - 1}{n_o} = \frac{H\text{-}p}{H} = 1 - \frac{p}{H} = \eta_{A\text{-}E}, \tag{34}$$

which obviously means the lowest efficiency of a friction source of heat, that is, $1 - \eta_{max} = p/H$.

This discussion implies friction heat and work of mechanical dissipation are interrelated. In the friction of solids that leads to wear, mechanical work cannot be fully converted into heat, just like heat cannot be fully converted into mechanical work. It is demonstrated as well values of friction heat and work of mechanical dissipation are determined by the ratio of unit pressures against the nominal and real surfaces of solid contacts. A parallel obtains, therefore, between the limited potential for converting mechanical work into heat as part of Afanasyeva-Ehrenfest thermodynamic cycle and in real tribological processes.

ON THE THERMODYNAMIC APPROACH TO TRIBOMETRY

From the physical point of view, friction is a thermodynamic process. Therefore, thermodynamic dependences and quantities should be used to analyse and describe this process. Tribology studies friction couples. They can be treated as open thermodynamic systems. Since energy is lost in the immediate vicinity of a friction contact, restricting the system to this area is recommended. This procedure is illustrated in **Fig. 8**. The volume of an object studied is determined by friction zone heights h_{R1}, h_{R2} and nominal contact surface of solids with dimensions a·b, where a is co-directional with friction velocity v. Heights of friction zone (volume) are defined in **[L. 14]** and described as follows, each for friction couple elements 1 and 2:

$$h_{R1} = \frac{ap}{H_1} \ , \tag{35}$$

$$h_{R2} = \frac{ap}{H_2} \ , \tag{36}$$

where H_1, H_2 – material hardness of the first and second friction element. Heights of friction zone computed by (35) and (36) are important for designing of wear-resistant superficial layers. **Fig. 8b** shows energetic interactions in the tribological system under discussion.

In the case of solids friction in (12), both friction heat Q_{dyss} and the work of mechanical dissipation A_{dyss} need to be addressed and described as follows:

$$\Delta U = \Delta I + Q_{1\text{-}2} + Q_{dyss} + A_{dyss}, \qquad (37)$$
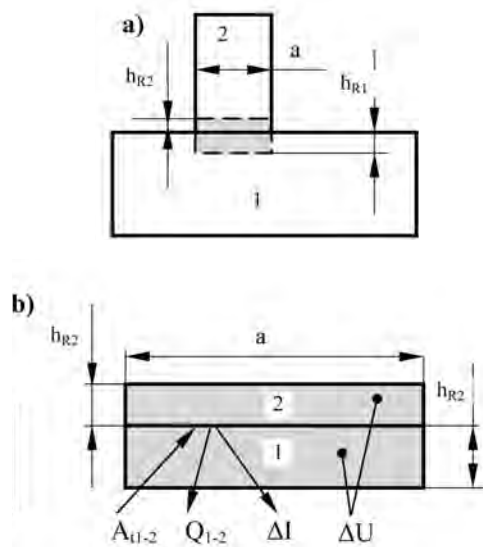
where technical work $A_{t1\text{-}2} = Q_{dyss} + A_{dyss}$ is synonymous with work of friction. Reversible work is ignored. Components of friction work can be described with (31):

– Friction heat

$$Q_{dyss} = A_{t1\text{-}2}(1 - kn_o), \qquad (38)$$

– The work of mechanical dissipation

$$A_{dyss} = A_{t1\text{-}2}kn_o. \qquad (39)$$

Fig. 8. **Boundary of a tribological system: a) made up of two friction elements 1 and 2 friction volume, b) where the friction volume of dimensions a·(h_{R1} + h_{R2}) constitutes the tribological system; friction path width b is perpendicular to the plane of the Figure**

Rys. 8. Granica systemu tribologicznego: a) w przypadku, gdy system tworzą dwa elementy trące 1 i 2 wraz z objętością tarcia, b) w przypadku, gdy objętość tarcia o wymiarach a·(h_{R1} + h_{R2}) stanowi system tribologiczny; szerokość ścieżki tarcia b jest prostopadła do płaszczyzny rysunku.

Wear coefficient k results from J.F. Archard's dependence, which describes volumetric wear V as follows:

$$V = k\frac{lN}{H}, \qquad (40)$$

where l – friction path.

Equation (37) characterises processes in a thermodynamic system that are caused only by friction work $A_{t1\text{-}2}$. Friction heat affects the growth of the system's internal energy, the growth of enthalpy, and the value of heat transferred to the environment. The work of mechanical dissipation also changes internal energy and enthalpy, but without having an impact on heat exchange with the environment. Thermodynamic parameters should be used in the design and discussion of tribological test results. These are first of all the quantities given in (37). Here, friction work can be affected via normal force. Power can be modified during friction by changing velocity of friction. The quantity of heat passing between the system and its environment can be varied, e.g., by means of heat exchangers. The remaining parameters of (37) – change of internal energy and enthalpy – are dependent variables that result from the energy balance. Since enthalpy variation is connected to tribological wear, according to (37), mass wear Δm is described by the following:

$$\Delta m = \frac{A_{dyss} + Q_{dyss} - Q_{1\text{-}2} - \Delta U}{i}, \qquad (41)$$

where specific enthalpy i quantitatively determines wear mechanism. Equation (41) implies cooling ($-Q_{1\text{-}2}$) fosters reduction of tribological wear. Beside the above parameters, intensive variables also play a major role in tribological studies. This is primarily true of temperature. Temperature, as well as pressure and velocity, describe only one point of the system at a given instant. Therefore, temperature measurement needs to be planned carefully in order to ensure reproducibility and comparability of friction test results. Temperature testing in stationary processes is recommended to ensure correct interpretation of its measured value. In line with the law of zero thermodynamics, temperature measurement requires the preservation of thermal equilibrium between a sensor and a selected point of the system. Sensor placement as close to the friction surface as possible is recommended. Since a spatial area of energy dissipation (**Fig. 8**) is a frictional source of heat, temperature cannot characterise thermal states of a tribological system unambiguously **[L. 15]**. Publication **[L. 16]** proposes describing a steady thermal state of a system with maximum temperature gradient. Analysis of the temperature gradient addresses the dual nature of energy dissipation caused by friction of solids.

CONCLUSION

The discussion above suggests the following conclusions:
- In the thermodynamic perspective, the lack of equilibrium and the irreversibility of physical processes are the main reasons for friction and wear.
- A model of the simple solid, universally employed in technical thermodynamics, must be modified for friction of solids – when wear is analysed, surface energy and volumetric work of mechanical nature must be taken into consideration.
- The first law of phenomenological thermodynamics for open systems should serve as the foundation

for the interpretation and analytical description of friction and its associated effects.

- A friction couple can be treated as a thermodynamic system; however, it is better to restrict this system to an area surrounding the friction contact – **Fig. 8**. Where energy dissipation takes place directly, secondary processes resulting from friction are omitted in this way.
- Friction heat and the work of mechanical dissipation may vary within the limits described by (32) and (34).
- In the case of solid friction, most mechanical work converted into friction heat is equal to heat in the Afanasyeva-Erhenfest cycle.
- Tribological testing and analysis of its results should address the important difference between heat released to the environment and friction heat.
- A friction couple forms a system of solids in pressure non-equilibrium as it comprises two surfaces – nominal and real – where different unit pressures prevail in these conditions, wear is associated with volumetric work.

TERMINOLOGY

a – length of the smaller friction element measured in the direction of friction velocity [m],

a_x – linear dimension of elementary contact surface of irregularities which is perpendicular to a [m],

A_r – real contact surface of solids in friction [m²],

A_n – nominal contact surface of solids in friction [m²],

A – work [J],

A_{1-2} – work of the transformation between states 1 and 2 [J],

A_{t1-2} – technical work (friction work) [J],

A_{dyss} – work of mechanical dissipation [J],

A_{tod} – reversible portion of technical work [J],

A_{dyssV} – volumetric part of dissipation work A_{dyss} [J],

A_{dyssF} – superficial component of dissipation work A_{dyss} [J],

δA_{dyss} – elementary work of mechanical dissipation [J],

δA_F – elementary superficial work [J],

δA_V – elementary volumetric work [J],

A_z – work of Carnot cycle [J],

b – width of friction path [m],

b_x – dimension of elementary contact surface of irregularities which is perpendicular to a [m],

e_F – specific surface energy [J·m⁻²],

F – surface [m²],

h – linear wear [m],

h^* – apparent linear wear [m],

h_R – height of friction zone [m],

H – hardness of the softer friction couple material [MPa],

H_1, H_2 – material hardness of the first and second friction element [MPa],

i – specific enthalpy [J kg⁻¹],

ΔI – enthalpy variation [J],

k – wear coefficient,

l – friction path [m],

m – mass [kg],

$\dot{m}$ – flux of wear product mass [kg s⁻¹],

Δm – mass wear [kg],

n_k – critical number of contacts,

n_o – number of real irregularity contacts on the nominal contact surface,

n_V – number of friction particles generated on the nominal contact surface,

N – normal force [N],

Q_{1-2} – heat [J],

Q_{diss} – heat of dissipation [J],

Q_{c1-2} – total heat [J],

Q_z – heat of Afanasyeva-Ehrenfest cycle [J],

δQ_F – elementary heat increment on the surface produced [J],

p – nominal surface pressure [MPa],

P – force [N],

ds – elementary piston displacement [m],

dS – entropy increment [J·K⁻¹],

T – friction force [N],

ΔU – internal energy increment [J],

dU_F – superficial energy increment [J],

V – volume, volumetric wear [m³],

V^* – apparent volume of wear [m³],

v – friction velocity [m·s⁻¹],

δ – no-form,

η – efficiency,

η_c – efficiency of Carnot cycle,

η_s – system efficiency,

η_{A-E} efficiency of Afanasyeva-Ehrenfest cycle,

μ – friction coefficient,

μ_i – chemical potential of ith component [J·kg⁻¹],

ρ^* – apparent density [kg·m⁻³],

ρ – density [kg·m⁻³],

Θ – temperature [K],

1-2 – designation of thermodynamic transformation's start and end,

1, 2 – index of friction couple element.

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