ISSN 0208-7774 TRIBOLOGIA 1/2021 p. 27–37
DOI: 10.5604/01.3001.0015.4898

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A DISCUSSION ON THE PHYSICAL INTERPRETATION OF MEASUREMENTS OF TRIBOLOGICAL WEAR

ROZWAŻANIA O FIZYCZNEJ INTERPRETACJI MIAR ZUŻYCIA TRIBOLOGICZNEGO

Key words: intensity of wear, wear resistance, energy distribution, systemic approach, physical interpretation, laws of energy and mass conservation, comparability, reproducibility, tribometry.

Abstract: Physical sense and practical significance of major measurements of tribological wear are analysed here. Definitions and methods of assessing these measurements are proposed on the basis of the laws of energy and mass conservation. Contributions of energy and displacement of particular friction forces corresponding to each element of a friction couple are addressed. Energy expenditure that causes wear is introduced into the definition of wear resistance. Planning and thermodynamic analysis of a tribological experiment and the application of thermodynamic concepts and quantities to the description and the interpretation of results are recommended. The author believes application of wear measures that have an unequivocal physical interpretation will limit problems with the incomparability and the irreproducibility of tribological results and issues with transferring them to real objects.

Słowa kluczowe: intensywność zużywania, odporność na zużycie, rozkład energii, podejście systemowe, interpretacja fizyczna, zasady zachowania energii i masy, porównywalność, odtwarzalność, tribometria.

Streszczenie: W niniejszej pracy zanalizowano senes fizyczny i praktyczne znaczenie ważniejszych miar zużycia tribologicznego. Zaproponowano definicje i sposoby oceny tych miar w oparciu o zasady zachowania energii i masy. Uwzględniono w nich udział energii i przemieszczenia poszczególnych sił tarcia, które przypadają na każdy z elementów pary ciernej. Do definicji odporności na zużycie wprowadzono nakład energii, który je spowodował. Zalecono zaplanowanie eksperymentu tribologicznego z jego analizą termodynamiczną oraz wykorzystanie pojęć i wielkości termodynamicznych do opisu i interpretacji uzyskanych wyników. Zdaniem autora stosowanie miar zużycia mających jednoznaczną interpretację fizyczną ograniczy problemy nieporównywalności i nieodtwarzalności wyników badań tribologicznych oraz trudności ich przenoszenia na obiekty rzeczywiste.

INTRODUCTION

Machine parts in friction change their initial dimensions due to tribological wear. This substantially restricts their life and reliability. Wear of both a friction couple element and a friction couple as a whole can be evaluated. The extent of this wear is expressed with absolute or relative measurements. The absolute measurement of wear **Z** can be volume V, mass m, gravity G of separated material, and thickness h of a separated or deformed layer. The absolute measurement is used rarely, because it fails to address operating conditions. Therefore, relative measures of wear are employed as a rule. These include the intensity of wear J, the relation of change in volume, mass, gravity, or the linear dimension of a specimen to a unit of time, friction path, work of friction, etc.

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Assessment of tribological wear and its intensity is basic information about the work of machine and mechanical equipment. Laboratory results of selected systems of solids in friction or lubricated friction reported by different researchers are only comparable to limited extents. It is all the more difficult to transfer these results directly to real objects. This state of affairs is a result of both the complexity of the friction process and methods of research, including the great diversity of test stands and the interpretation of results used to describe tribological wear. Tribometric issues are discussed at length by M. Grebe **[L. 1]**, among others.

This paper will analyse physical interpretation of quantities characterising tribological wear and determine the measurements that can be interpreted in this way. The significance of common tribological measurements arises chiefly from the fact they are relatively easy to quantify and acceptable intuitively. For instance, the "linear wear of an element," measured in micrometres, caused on a friction path expressed in kilometres, makes no physical, but only technical sense. In turn, defining wear resistance as the reverse of wear or wear intensity is narrow from the physical perspective, since the energy expenditure causing the tested wear is ignored. An analytical description of wear intensity is governed by the laws of energy and mass conservation. Such a description should produce guidance for the planning of experimentation and the interpretation of its results. A correct interpretation and calculation of wear intensity is reflected in the assessment of the wear resistance of both a selected friction couple element and of a friction system as a whole. A systemic approach to the analysis of tribological wear needs to solve the problem of contributions of the particular friction couple elements to the process of energy dispersion, which is equal to work of wear. In this manner, displacements and velocities of the particular friction forces acting on each separate element in friction can be determined. Explanation of these issues gives rise to novel proposals for assessment of tribological wear, especially in experimental testing, which will contribute to improvement of comparability and reproducibility of the results.

THE QUESTION OF THE PHYSICAL INTERPRETATION OF SELECTED MEASUREMENTS OF TRIBOLOGICAL WEAR

Tribological literature offers a range of definitions for wear intensity. Some major ones are covered in this section in order to establish their physical and practical significance. **Figure 1** schematically shows Elements 1 and 2 in friction, acted upon by a normal force N and travelling at a relative velocity v. The nominal surface of their contact A_n has the dimension a – directed like the friction velocity v. The friction path of element 1 in relation to 2 is $l = \kappa \cdot a$. Two forces act on the contact of solids and perform work – an active force P and a reactive force T. Assuming for the sake of illustration that these forces and v are independent from time, work of P can be expressed as $A_p = P \cdot l$. To the contrary, the action of T is negative, that is, the work of friction is $A_t = -T \cdot l$. In this system of solids, work is the sum total of $A_p + A_t = 0$ given $P = -T$. This means a total dissipation of energy generated by P. **Figure 1** also presents the linear wear of the individual elements. Along the path of friction equal to the dimension a, wear of the first element is h_{o1} and of the other h_{o2}, while, on Friction Path l, the wear of the first element is h_1. The linear wear obviously corresponds to volume V, mass m, or gravity G of separated material. This discussion continues to employ a general symbol **Z** as a measurement of tribological wear. The literature commonly adopts the mean intensity as a relation of **Z** to the time of friction t or to the path of friction l. Application of the mean wear is only reasonable where work is stationary. If wear intensity depends on time, e.g., in the phase of breaking in, the application of momentary wear intensity is recommended.

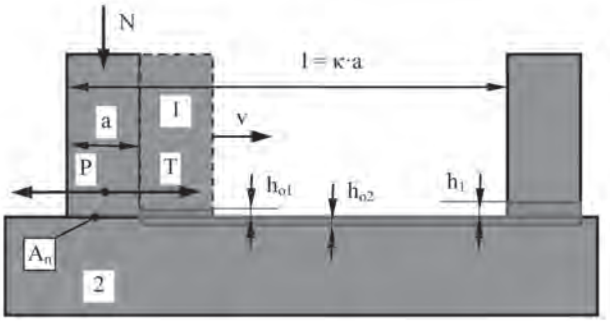

Fig. 1. A schematic representation of elements 1 and 2 in friction and their linear wear h

Rys. 1. Schematyczne przedstawienie elementów trących 1 i 2 i ich zużycia liniowego h

The subsequent dependences describe intensity of wear as follows:

Averaged over time t:

$$J_{(1)} = \frac{\mathbf{Z}}{t}, \tag{1}$$

Momentary:

$$J_{(2)} = \frac{d\mathbf{Z}}{dt}, \tag{2}$$

Averaged relative to Friction Path l:

$$J_{(3)} = \frac{\mathbf{Z}}{l}, \tag{3}$$

Momentary relative to Friction Path dl:

$$J_{(4)} = \frac{d\mathbf{Z}}{dl}. \tag{4}$$

The units of wear intensities $J_{(1)}$ and $J_{(2)}$ are $m^3 \cdot s^{-1}$, $g \cdot s^{-1}$, $G \cdot s^{-1}$ and $m \cdot s^{-1}$, respectively, depending on the measurements of **Z** applied. Physical interpretation of both these quantities is comprehensible and unambiguous. These are averages or momentary fluxes (flow intensities) of volume, mass, gravity, or the linear dimension, respectively. Formulas (3) and (4) imply the units of intensities $J_{(3)}$ and $J_{(4)}$ are m^2, $g \cdot m^{-1}$, $G \cdot m^{-1}$, and 1, respectively, if the friction path is measured in metres. The physical interpretation of (3) and (4) is no longer as simple and evident as in the two preceding cases. Since $l = v \cdot t$, the relations obtain, $J_{(1)} = v \cdot J_{(3)}$; $J_{(2)} = v \cdot J_{(4)}$. $J_{(3),}$ is the courses of physical or geometrical quantities $J_{(1)}$ divided by friction velocity v. In turn, $J_{(4)}$ equals the flux of the physical or geometrical quantity $J_{(2)}$ divided by v. This means $J_{(3)}$ and $J_{(4)}$ are no longer flow intensities. They are of negligible use to explication or description of the physics of wear. The definitions (3) and (4) have only practical significance. They help to illustrate material wastage after a specific path of friction in a simple way. The "linear intensity" I_h, commonly used by literature to express the relation of linear wear h to friction path l, is a special variant of wear intensity $J_{(3)}$ **[L. 2**, **3]**:

$$I_h = \frac{h}{l} \tag{5}$$

Formulas (1) – (5) contain the same amount of information about intensity of tribological wear, provided that v is known. An energetic analysis of friction and wear by G. Fleischer **[L. 4]** has detected a connection between shear stress $\tau = T/A_n$ on the nominal surface A_n and density of friction energy e_R^* (*scheinbare Reibungsenergiedichte*), which is a relation of friction work A_t to volume V of worn material, described as follows:

$$I_h = \frac{\tau}{e_R^*}. \tag{6}$$

Thus, the linear intensity of wear I_h indirectly brings information about work of friction, volumetric wear, and unit friction resistance. However, expressing it solely as linear wear divided by friction path blurs information about the quantities present in (6). I_h can be derived from (6), yet the components τ and e_R^* cannot be determined from (5).

Definitions (1–5) fail to address the nominal contact surface of solids in friction. A formula for average wear intensity including the nominal friction surface A_n is given below:

$$J_{(6)} = \frac{\mathbf{Z}}{l \cdot A_n}. \tag{7}$$

1, $g \cdot m^{-3}$, $G \cdot m^{-3}$, m^{-2} can be units of $J_{(6)}$, respectively. The "specific wear" $J_{(7)}$ is a special case of the above dependence. It relates to friction in individual contact of surface asperities of a contact surface A_{ri}. Elementary wear V_{el} arises on an elementary microscopic asperity displacement l_{el}. This definition has been authored by I.V. Kragelski **[L. 2]**, who expresses it as follows:

$$J_{(7)} = i_h = \frac{V_{el}}{l_{el} A_{ri}}. \tag{8}$$

$J_{(7)}$ is a non-dimensional quantity, also known as the specific linear intensity of wear i_h. The definitions (7) and (8) are produced by expanding on (3) to make them more precise as they consider the surface area from which wear products originate. However, these quantities do not have unequivocal physical meaning.

Reference **[L. 3]** cites one more description of wear intensity, defined as a unit volumetric wear $J_{(8)}$:

$$J_{(8)} = \frac{V}{Nl}, \tag{9}$$

where N is the normal load of a friction couple. $m^2 \cdot N^{-1}$ is the unit of intensity $J_{(8)}$. This quantity has no physical interpretation and can only have a practical significance. As far as $J_{(3)}$ is concerned, the above definition better characterises friction and wear as it addresses the value of normal load N. The introduction of the friction coefficient μ produces an even more accurate description of wear intensity, namely:

$$J_{(9)} = \frac{\mathbf{Z}}{\mu N l}. \tag{10}$$

This is the reverse of energy density, since **Z** is V, and the reverse of the specific work of wear when **Z** is the mass of wear products m. Thus, intensity $J_{(9)}$ characterises susceptibility to tribological wear from an energetic perspective.

V.V. Fedorov et alia **[L. 5]** employ the "unit intensity of wear," described as follows:

$$J_{(10)} = \frac{dV}{A_n dt}. \tag{11}$$

This is in turn a modification of (2) where the contact surface A_n is taken into account. The unit of $J_{(10)}$ is $m \cdot s^{-1}$. It can be said to be the density of wear products volumetric flux (indirectly, of mass, gravity, and linear dimension of a solid). Therefore, $J_{(10)}$ can be interpreted unambiguously in physical terms. Density of $J_{(10)}$ is a certain mean value relative to A_n. Wear intensity can be expressed more accurately in the following manner:

$$J_{(11)} = \frac{d^2V}{dA_n dt}. \tag{12}$$

To sum up this review of selected common definitions of wear intensity, they can be said to differ markedly from one another. A majority have no physical interpretation. Only (1) and (2) can be interpreted explicitly as fluxes of physical or geometrical quantities or as densities of these fluxes – see (11) and (12). $J_{(10)}$, on the other hand, is characterised by a material's susceptibility to wear caused by friction. Formula (12) describes the intensity of wear in most detail. For instance, integration of (12) can produce (11); whereas, a reverse procedure is impossible. $J_{(11)}$ has a primarily theoretical significance. For practical reasons, it is hard to use (12) at the current stage of measurement technology. In the circumstances, a compromise solution looks as follows:

$$J_{(12)} = \frac{\mathbf{Z}}{A_n t}. \tag{13}$$

This is the mean density of tribological wear flux **Z**. Measurement of the values in the above formula is no longer difficult. I have used (12) and (13) in **[L. 6–9]**, among other publications.

The key definitions of wear intensity covered in this section apply only to a selected element of a friction couple. Thus, the entire path or work of friction is attributed only to a single element (specimen). The fact the other element of a friction couple is involved in the process of energy dissipation is involved as well is ignored. This is reflected, inter alia, in characteristics of wear intensities of selected machine parts or laboratory samples given in the literature.

DISTRIBUTION OF ENERGY AND WEAR BETWEEN SOLIDS IN FRICTION

This section is devoted to determining contributions of each friction element to the process of energy dissipation. Work of friction by friction couple elements is the path times the force of friction acting on the same element. Establishing values of both of these factors provides the grounds for assessing real intensity of wear of an individual tribological system element. **Figure 2** presents a diagram of friction elements 1 and 2. Two forces of friction, T_1 and T_2 (where $T_1 = -T_2$), operate in their contact, with each performing a work of friction A_{t1} and A_{t2}, respectively.

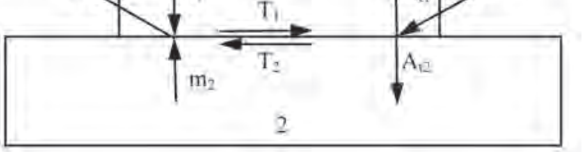

Fig. 2. Schematic representation of solids 1 and 2 in friction, marking their mass wear m_1, m_2 and the energy they dissipate, equal to the works of friction A_{t1} and A_{t2} [L. 10, 11]

Rys. 2. Schematyczne przedstawienie trących się ciał 1 i 2 z zaznaczeniem ich zużycia masowego m_1, m_2 oraz rozproszonej przez nie energii równej pracom tarcia A_{t1} i A_{t2} **[L. 10, 11]**

These are components of the total work of friction A_t. In line with the law of conservation, the energy balance is described as follows:

$$A_t = A_{t1} + A_{t2}. \tag{14}$$

The entire work of friction causes mass m wastage in the friction couple, while the components of this work cause the wastages m_1 and m_2, respectively. According to the law of mass conservation, the following total results:

$$m = m_1 + m_2. \tag{15}$$

A physical quantity defined as specific work of wear e_R^x serves to determine components A_{t1} and A_{t2} of work of friction. This is the work of friction in relation to mass wear. In the case of a friction couple **[L. 7, 10, 11]**:

$$e_R^x = \frac{A_t}{m} \tag{16}$$

and its elements:

$$e_{R1}^x = \frac{A_{t1}}{m_1}, \tag{17}$$

$$e_{R2}^x = \frac{A_{t2}}{m_2}. \tag{18}$$

(14) can be formulated as follows, in consideration of (16) – (18):

$$me_R^x = m_1 e_{R1}^x + m_2 e_{R2}^x. \tag{19}$$

Where (14) and (15) are fulfilled at the same time, the specific works of wear are equal **[L. 10, 11]**:

$$e_R^x = e_{R1}^x = e_{R2}^x. \tag{20}$$

[L. 11] demonstrates (20) is the only acceptable solution to (14), (15), and (19) from the physical point of view (16) – (18), (20) imply each friction couple element performs the following work **[L. 11]**:

$$A_{t1} = \frac{m_1}{m} A_t, \tag{21}$$

$$A_{t2} = \frac{m_2}{m} A_t. \tag{22}$$

This discussion assumed stationary friction on the boundary of solids 1 and 2. The intensity of wear is defined for this case of friction. If friction velocity and friction forces vary in time, their mean values relative to the total time of friction must be adopted.

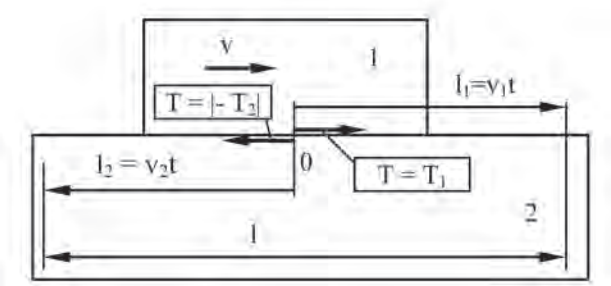

Fig. 3. Illustration of friction forces T_1, T_2 and their corresponding friction paths l_1, l_2 along which they perform works A_{t1} and A_{t2}, respectively [L. 11]

Rys. 3. Ilustracja sił tarcia T_1, T_2 i odpowiadających im dróg tarcia l_1, l_2, na których wykonują one prace odpowiednio A_{t1} i A_{t2} **[L. 11]**

Figure 3 shows the friction elements 1 and 2, acted upon by friction forces T_1 and T_2 with velocities v_1 and v_2 along friction paths l_1 and l_2 whose sum total is equal to the total path of friction l. Therefore, each of these friction forces acts on displacement l with a slip. The shift for T_1 is the relation l_1/l, for T_2, l_2/l. The total work of friction A_t is equal to $T \cdot l$ and its components: $A_{t1} = T \cdot l_1$ and $A_{t2} = T \cdot l_2$. Considering (21) and (22), l_1 and l_2 are determined as follows **[L. 11]**:

$$l_1 = \frac{m_1}{m} l, \tag{23}$$

$$l_2 = \frac{m_2}{m} l. \tag{24}$$

Components of the friction velocity are calculated in a similar manner **[L. 11]**:

$$v_1 = \frac{m_1}{m} v, \tag{25}$$

$$v_2 = \frac{m_2}{m} v. \tag{26}$$

In this section, the fundamental tribological terms like work, path, and the velocity of friction are analysed from the energetic point of view. Two forces acting on two solids in a friction zone are found to perform different works at different velocities (powers of friction). There is a proportionality between a shift of friction force on a given friction couple element and the relative displacement of solids in friction, mass wear of the element, and the reverse mass wear of the friction couple. There is also a proportionality between the velocity of friction force travelling along a given friction couple element and relative velocity of solids in friction, mass wear of the element, and the reverse mass wear of the friction couple.

A friction force acting upon friction couple elements moves in relation to these elements and performs some work along its path. Friction contact occurs with both the friction forces and the work of force corresponding to a given friction element is performed with a shift along the entire relative displacement. The shift depends on mass wastage of the element and overall mass wear of the friction couple. Wear particles, which do not slide but roll in friction zones, are responsible for this shifting effect.

Formula (20) also produces the following unique case of a tribological process. Namely, if no visible wear takes place on either solid, e.g., the second, the velocity and path of the friction force acting on this solid are approximately zero. Thus, wear of the first element is approximately the same as wear of the friction couple. The velocity and path of a friction force acting on a wearing element correspond to the velocity and path of relative displacement of solids in friction. This case is illustrated, for instance, with the formation of a chalk line on a blackboard. This example shows testing can be limited to a selected element of a friction couple only conditionally, that is, where its hardness is significantly lower than of a partner material. Wear resistance in this specific case is described with specific works of wear as follows:

$$e^x_R = \frac{A_t}{m} = e^x_{R1} = \frac{A_{t1}}{m_1} = e^x_{R2} = \frac{0}{0} = \text{const, since: } m = m_1,$$

$m_2 = 0$, $A_t = A_{t1}$; $A_{t2} = 0$.

A PROPOSED DEFINITION OF WEAR INTENSITY OF TRIBOLOGICAL SYSTEM ELEMENTS

The methods of defining and calculating wear intensity applied by the literature till now fail to address contribution of the particular friction elements to work of friction. For instance, linear intensity I_h of a selected element is expressed as a relation of its linear wear to the total path of friction. In this way, the entire work of friction is implicitly attributed to the wear of this element, although the other element is also involved in energy dissipation. This section aims to describe wear intensity more precisely and considering the law of mass and energy conservation. Volumetric wear V of a friction couple element will be described with J.F. Archard's dependence **[L. 12]** in the following manner:

$$V = klA_r = kl\frac{N}{H}, \tag{27}$$

where: k – wear coefficient, l – total path of friction, A_r – real contact surface of solids, N – normal load of friction couple, H – hardness of the softer material of friction couple element. This formula is of a great practical significance owing to its simplicity. Its physical rationale needs to be stressed as well. The likelihood of wear particle separation from the friction element material described quantitatively with k is of particular importance. The coefficient k can be derived from (27) and expressed as the specific linear intensity of wear i_h, namely:

$$k = \frac{V \cdot H}{N \cdot l} = \frac{A_n \cdot h \cdot H}{A_n \cdot p \cdot l} = I_h\frac{H}{p} = i_h, \tag{28}$$

where:
p – unit pressure against the nominal surface A_n.

The significance of (27) to the analysis of wear intensity results from clarity of the dependence between wear, the path of friction, and real contact surface of solids. In addition, the proposed theoretical approach enables a general analysis of wear intensity. Quantitative evaluation of wear will proceed to specific examples. J.F. Archard's formula can be extended to each friction couple element assuming friction particles are present in their contact whose hardness is greater than the material hardness of either element. **Figure 4** is a schematic illustration of a fragment of the contact zone of elements 1 and 2 in a tribological system showing a particle of wear product 3. It is noted the top element 1 travels at a constant velocity v to the right in relation to element 2. Particle 3 acts on solid 2 with an active force T_{2i} associated with a friction force, T_{2i}, in the opposite direction. In turn, particle 3 acts on solid 1 with an active force T_{1i}, accompanied by a passive force of friction T_{1i}. In friction, the intermediate element moves relative to solids 1 and 2, causing tribological wear. This is represented with lines whose lengths are l_{1i} and l_{2i}. Particle 3 travels with a velocity v_{2i} in relation to the bottom element and v_{1i} in relation to the top element. The work of friction A_{t1i} may be treated as an energetic effect of elementary mechanical interactions that cause wear when forming a groove with a length of l_{1i}; performance of work A_{t2i} when forming a groove with a length of l_{2i} can be seen likewise. Hence, interpreted microscopically (at the level of surface micro asperities), A_t is the sum total of elementary works: $A_{t1} = \sum_{1}^{n} T_{1i} l_{1i}$ and $A_{t2} = \sum_{1}^{m} T_{2i} l_{2i}$, where *n* and *m* are the numbers of grooves on friction elements 1 and 2, respectively. Macroscopically, the displacement occurs along the friction zone with two friction forces T_1 and T_2, and this corresponds to a total relative displacement of the friction element 1 – **Figs. 1** and **3**.

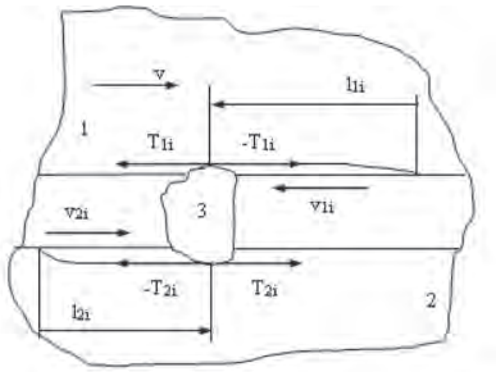

Fig. 4. Schematic explicating mechanical effects of elements 1 and 2 via the wear particle 3 [L. 9]

Rys. 4. Schemat objaśniający oddziaływanie mechaniczne elementów 1 i 2 za pośrednictwem cząstki zużycia 3 **[L. 9]**

After an appropriate friction path is attributed to the elements 1 and 2, their volumetric wear can be described as follows:

$$V_1 = k_1 l_1 A_{r1} = k_1 l_1 \frac{N}{H_1} = k_1 \frac{m_1}{m} l \frac{N}{H_1}, \tag{29}$$

$$V_2 = k_2 l_2 A_{r2} = k_2 l_2 \frac{N}{H_2} = k_2 \frac{m_2}{m} l \frac{N}{H_2}, \tag{30}$$

where: H_1 and H_2 – hardnesses of element 1 and 2 materials. The dependence $l = l_1 + l_2 = l(m_1/m) + l(m_2/m)$ applies of course.

Formulas (29) and (30) serve to describe volumetric wear intensity of solids 1 and 2 as relations of the volumetric wear and an appropriate friction path, as defined by (3):

$$\frac{V_1}{l_1} = \frac{A_n h_1 m}{l m_1} = I_{h1} A_n \frac{m}{m_1} = k_1 \frac{N}{H_1} \tag{31}$$

$$\frac{V_2}{l_2} = \frac{A_n h_{o2} m}{a m_2} = I_{h2} A_n \frac{m}{m_2} = \frac{A_n h_{o2} \kappa m}{l m_2} = k_2 \frac{N}{H_2} \tag{32}$$

If linear wear h is taken into consideration instead of volumetric wear V, the following can be expressed:

$$\mathbf{I_{h1}} = \frac{h_1}{l_1} = \frac{h_1 m}{l m_1} = I_{h1} \frac{m}{m_1} = k_1 \frac{p}{H_1}, \tag{33}$$

$$\mathbf{I_{h2}} = \frac{h_2}{l_2} = \frac{h_{o2} m}{a m_2} = \frac{h_{o2} \kappa m}{l m_2} = I_{h2} = \frac{m}{m_2} = k_2 \frac{p}{H_2}, \tag{34}$$

where linear wear intensities $I_{h1} = h_1/l$ and $I_{h2} = h_{02}/a$ currently defined by the literature; the linear wear intensities introduced here, on the other hand, are designated $\mathbf{I_{h1}}$, $\mathbf{I_{h2}}$. They are calculated addressing contributions of both the friction elements to energy dissipation. (33) and (34) result in the following inequalities:

$$\mathbf{I_{h\,1}} > I_{h1} \tag{35}$$

and

$$\mathbf{I_{h2}} > I_{h2}. \tag{36}$$

This section proposed an original method for evaluation of wear intensity that addresses contributions of both friction couple elements to energy dissipation. When determining linear wear intensity, not only relative displacement of solids but also displacements of friction forces acting upon the particular solids are taken into account. The dependence between masses of material used by a selected friction element and total mass wear of the friction couple plays an important role in (29)–(36). The introduction of the two wear coefficients, k_1 and k_2, is important as well.

COMMENTS CONCERNING MEASUREMENTS OF WEAR RESISTANCE

Resistance to tribological wear is defined as a material property that characterises its resistance to detachment of wear particles from its superficial layer in certain operating conditions. The resistance is normally measured as the reverse of wear or of wear intensity **[L. 13, 14]** – one of the dependences (1)–(13) can be used to describe it.

The unit of wear resistance obviously depends on a selected definition of wear intensity. For practical reasons, relative resistance to wear is occasionally employed, defined as the relation of wear resistance of a tested material and of a reference (standard) material. This is a dimensionless quantity in the event. Its drawback is that the same test conditions cannot be maintained when testing a variety of materials and a given specimen. This complicates comparability and reproducibility of test results. The methods of assessing wear resistance listed above refer to a selected material. Of course, the wear resistance of an entire friction couple can be analysed as well. To this end, the total tribological wear must be considered. The usual approach to defining wear resistance relies on mechanistic laws. This author recommends a more general, thermodynamic description of wear and its derivative characteristics. This approach is supported by the fact the current measurements of wear resistance only include values of wear. The amount of energy expended on this wear is ignored in this way. Thus, the same wear resistance can be demonstrated for two test materials with differing energy expenditures. In addition, what matters is not only the energy expenditure alone, which corresponds to work of friction, but also its structure. The energy balance in the tribological system is described with the equation of the first law of thermodynamics for open systems. The equation is as follows **[L. 15]**:

$$\Delta U = -\Delta I - Q_{1\text{-}2} + A_{t1\text{-}2} = -i\Delta m - Q_{1\text{-}2} + A_{t1\text{-}2}, \quad (37)$$

where: ΔU – increment of the system's internal energy, ΔI – increment of enthalpy, $Q_{1\text{-}2}$ – energy discharged from the system to its environment as heat, $A_{t1\text{-}2}$ – technical work equal to work of friction A_t, and – mean specific enthalpy characterising the wear mechanism, Δm – mass of material removed from the thermodynamic system. (37) refers to a friction couple treated as a thermodynamic system.

Equation (37) directly implies a dependence of the mass of worn material on a variety of energetic impacts, namely **[L. 15]**:

$$\Delta m = \frac{-\Delta U - Q_{1\text{-}2} + A_{t1\text{-}2}}{i}. \quad (38)$$

In light of the foregoing dependence, wear depends not only on the work of friction but also on the amount of heat exchanged with the environment and change of the friction couple's internal energy, identified with the open thermodynamic system. The wear mechanism is important as well, dependent not only on the type of worn material but also on conditions and parameters of friction and impact of the chemical environment on the contact surface of solids. Mean specific enthalpy of wear products 'i' is a quantitative characteristic of the wear mechanism. It depends on the above factors. The law of tribological wear (38), derived directly from the first law of thermodynamics, is a specific formulation of the law. It explains impact of the particular energetic effects on the value of friction wear. The system's mass wastage Δm is an absolute measurement of wear. In order to characterise the wear process, application of a relative measurement is recommended – intensity as defined by (1), (2) or possibly (13).

Like volumetric wear of friction couple elements is described with (29) and (30), (38) can serve to describe their mass wear, namely:

$$\Delta m_1 = \frac{-\Delta U_1 - Q_{1\text{-}21} + A_{t1\text{-}21}}{i_1}, \quad (39)$$

$$\Delta m_2 = \frac{-\Delta U_2 - Q_{1\text{-}22} + A_{t1\text{-}22}}{i_2}. \quad (40)$$

In the foregoing cases of wear description, each friction couple element is treated as an open thermodynamic system. Mass wear of the system is $\Delta m = \Delta m_1 + \Delta m_2$. (38)–(40) imply reproducibility of wear in tribological testing is conditional on all the quantities in these equations maintaining the same values. It's very difficult to meet these conditions.

This author believes it is necessary to apply the thermodynamic laws to definitions of wear resistance measurements. This requirement is fulfilled by the specific work of wear. Its analytical description is derived from (16) on introduction of (38) **[L. 9]**:

$$e_R^x = \frac{i}{1 - \frac{\Delta U + Q_{1\text{-}2}}{A_{t1\text{-}2}}}. \quad (41)$$

The above expression implies wear resistance is conditioned by the wear mechanism (characterised by specific enthalpy 'i'), the change of the system's internal energy ΔU, and heat provided by the system to its environment $Q_{1\text{-}2}$ given a specified work of friction $A_{t1\text{-}2}$. The resistance is therefore not the only property of a tested material but of the tribological system and depends on conditions and parameters of the friction process. Thus, each element is characterized by the same specific work of wear – as per (20). It should be added specific enthalpy of wear products is another systemic quantity and a measurement of wear resistance. This means it is equal in a friction system of solids and its individual elements **[L. 9, 16]**:

$$i = i_1 = i_2. \qquad (42)$$

(42) is derived like (20). Values of 'i' can only be established in extremely complicated calorimetric testing. This quantity as a measurement of wear resistance has no practical significance; therefore, (41) offers the possibility of increasing wear resistance by controlling thermal processes with a heat exchanger. Its maximum can be reached in stationary friction processes where the friction surface temperature is equal to the temperature characteristic of minimum wear **[L. 7]**. This theoretical conclusion is confirmed empirically with regard to eight different metal friction systems **[L. 17]**. This proves a significant role of the friction contact temperature, particularly in the process of stationary wear **[L. 18]**. Beside the temperature, maximum temperature gradient on the nominal contact surface of solids in friction is also important **[L. 19]**. This is one more premise showing wear resistance is a function of the tribological process, not exclusively of a tested material. This important fact should be taken into consideration in the planning and execution of tribological experimentation and interpretation of results.

CONCLUSIONS

This discussion draws attention to some causes of the incomparability and irreproducibility of results in testing of friction and wear on test stands and to difficulties with transferring these results to real machine elements. A number of methods of the evaluation and measurement of wear intensity are proposed. Only some have unequivocal physical interpretations and are suitable for formulation of analytical dependences describing friction and wear based on the law of mass and energy conservation. This author recommends planning of tribological testing to start with determination of energy interactions in a friction couple. A systemic approach needs to be adopted in order to define contributions of the particular tribological system elements to the processes of friction and wear. A friction couple should be treated as an open thermodynamic system. This implies application of thermodynamic concepts and quantities. This is due to the fact friction is a thermodynamic process. The restricted mechanistic approach prevails in the literature, meanwhile. Testing of tribological wear of only a selected system element fails to bring full information on friction, since the contribution of the other element to the process of energy dissipation is ignored. Paths of the particular friction forces are associated with wear values of each friction couple element. These components of the whole friction path provide the basis for determining wear intensity of the individual friction elements. This is necessary for the correct calculation of wear intensity. The linear intensities determined in this manner are greater than the intensities computed at present. Defining wear resistance as the reverse of wear or wear intensity fails to address friction work. Therefore, the application of specific work of wear as the measurement of this resistance is recommended. This easily quantifiable magnitude has a physical interpretation and is a function of thermodynamic quantities which are direct results of the equation for the first law.

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NOMENCLATURE

a – dimension of surface A_n with the same direction as friction velocity v [m],
A_r – real contact surface of solids in friction [m^2],
A_{ri} – area of surface asperity contact [m^2],
A_n – nominal contact surface of solids in friction [m^2],
A_t – friction work [J],
$A_{t1\text{-}2}$ – technical work (friction work) [J],
e_R^* – density of friction energy [$J \cdot m^{-3}$],
e_R^x – specific work of wear [$J \cdot kg^{-1}$],
G – gravity of wear products [N],
h – linear wear [m],
H – hardness of the softer friction couple material [MPa],
H_1, H_2 – hardnesses of the first and second friction couple element material [MPa],
i – specific enthalpy [$J \cdot kg^{-1}$],
i_h – specific linear wear intensity,
ΔI – enthalpy increment [J],

I_h – currently defined linear intensity of wear,
$\mathbf{I_h}$ – corrected linear intensity of wear,
J – generalised symbol of wear intensity,
k – wear coefficient,
l – friction path [m],
1_{el} – friction path in surface asperity contact [m],
m – mass wear [kg],
Δm – mass wastage of thermodynamic system [kg],
N – normal force [N],
$Q_{1\text{-}2}$ – heat [J],
p – nominal unit pressure [MPa],
P – force [N],
t – time [s],
T – friction force [N],
ΔU – internal energy increment [J],
Z – generalised symbol of tribological wear,
V – volumetric wear [m^3],
V_{el} – elementary volumetric wear [m^3],
v – friction velocity [$m \cdot s^{-1}$],
κ – quotient l/a,
μ – friction coefficient,
τ – shear stress [MPa],
1–2 – start and end of thermodynamic transformation,
1, 2 – index of friction couple element.