ISSN 0208-7774 TRIBOLOGIA 5/2019 p. 51–57
DOI: 10.5604/01.3001.0013.6561

Maria MACIĄG[*]

ANALYSIS OF THE RANGE OF THE SPECIFIC HEAT OF TRIBOLOGICAL WEAR PRODUCTS

ANALIZA ZAKRESU WARTOŚCI CIEPŁA WŁAŚCIWEGO POWSTAJĄCYCH PRODUKTÓW ZUŻYCIA TRIBOLOGICZNEGO

Key words: specific heat, friction, wear, energy balance, development of results.

Abstract This paper continues a discussion of specific heat cp’ of wear product material at the time of the products’ generation which was initiated in **[L. 2]**. The very high values of this quantity found on the basis of the laws of mass and energy conservation have inspired further analyses to possibly validate the results. System quantities C and D **[L. 2]** have played central roles in earlier modelling of the friction and wear of solids. They are determined for a certain range of the temperature of a macroscopic contact of solids Θ and serve the purpose of a merely approximate estimation of minimum cp’. An attempt at determining real values of cp’ for specific Θ without taking C and D into consideration has been undertaken in this study. The discussion was based on the energy balance equation for the stationary friction process which is associated with wear. The significance of friction parameters, the physical properties of a material subject to friction, and some characteristics of the tribological system have been emphasised. The analysis is also designed to determine maximum heat, cp’max, and a range of its variations, cp’min - cp’max. The resultant analytical dependences that characterise friction and its effects are illustrated with examples of selected experiments **[L. 10]**, which were originally designed to estimate values of cp’ **[L. 2]**. The evaluation of cp’ discovers negligible differences between cp’ and cp’min. Important information has additionally been acquired about the values of the flash temperature, Θo, and its relations to temperature D. No regular impact of on the specific heat of wear products has been determined.

Słowa kluczowe: ciepło właściwe, tarcie, zużycie, bilans energetyczny, opracowywanie wyników.

Streszczenie Niniejsza praca jest kontynuacją rozważań o cieple właściwym cp’ materiału produktów zużycia w momencie ich powstawania rozpoczętych w publikacji **[L. 2]**. Stwierdzone na podstawie zasad zachowania masy i energii bardzo duże wartości tej wielkości są inspiracją do przeprowadzenia dalszych analiz w celu ewentualnego potwierdzenia słuszności uzyskanych wyników. W dotychczasowym sposobie modelowania tarcia i zużywania ciał stałych główną rolę spełniły wielkości systemowe C i D **[L. 2]**. Są one wyznaczane dla pewnego zakresu temperatury styku makroskopowego ciał Θ i służą tylko przybliżonej ocenie minimalnej wartości cp’. W niniejszej pracy została podjęta próba wyznaczenia realnej wartości ciepła właściwego cp’ dla konkretnej wartości temperatury Θ bez uwzględniania wielkości C i D. Rozważania oparto na równaniu bilansu energii dla przypadku stacjonarnego procesu tarcia, któremu towarzyszy zużywanie. Podkreślono znaczenie parametrów tarcia, własności fizycznych materiału podlegającego zużywaniu oraz niektórych cech systemu tribologicznego. Celem rozważań jest także wyznaczenie maksymalnej wartości ciepła cp’max i ustalenie zakresu zmienności jego wartości cp’min – cp’max. Uzyskane zależności analityczne, charakteryzujące tarcie i jego skutki zilustrowano na przykładach wybranych badań eksperymentalnych **[L. 10]**, które posłużyły pierwotnie do oceny wartości ciepła właściwego cp’ **[L. 2]**. Ocena wartości ciepła właściwego cp’ pozwala stwierdzić znikome różnice między cp’ i cp’min. Ponadto uzyskano ważne informacje o wartościach temperatury błysku Θo i jej relacji w odniesieniu do temperatury D. Nie stwierdzono regularnego wpływu temperatury Θ na ciepło właściwe powstających produktów zużycia.

INTRODUCTION

It is the objective of this paper to develop a more detailed description of friction by the inclusion of real properties of matter exhibited when solids are subject to wear. The nature of the friction process is highly complex and conditioned by a great number of its parameters and a series of physical and chemical properties of substances directly and indirectly involved in the dissipation of mechanical energy. Therefore, the author has limited the

---

[*] ORCID: 0000-0001-6497-9260. Kazimierz Pulaski University of Technology and Humanities in Radom, Malczewskiego 20a Street, 26-600 Radom, Poland.

scope of this study to the analysis of only one physical quantity, specific heat. In this way, the paper becomes part of a cycle of discussions of dynamic properties of matter displayed only at the time of its dispersion. These properties can be expected to differ markedly from static properties listed in generally available physical and chemical tables. Experimental results, the chief source of information about real systems of bodies in friction, are the starting point for the proposed treatment. The available empirical knowledge is obviously insufficient for the purposes of defining quantitative relations among physical magnitudes that characterise transformations in a frictional contact. Thermodynamic analysis is a major addition to the examination of friction. Conclusions derived from the laws of mass and energy conservation, in particular, the first law of thermodynamics for open systems, supplemented with experimental results, lead to a quantitative description of phenomena in these systems **[L. 1]**. The description also gives rise to methodological indications for the design of tribological testing.

The eponymous analysis was first inspired by a model of thermal processes based on the assumption specific heat of wear products *in statu nascendi* is not markedly different to the specific heat of a solid substance prior to its fragmentation **[L. 1]**. A balance of fluxes of various forms of energy and mass in a tribological system and at its boundaries with the environment is expressed as an equation of the first law of thermodynamics for an open stationary system. Attention is drawn to a newly introduced, systemic quantity C, which is a product of the specific heat multiplied times the maximum temperature of the friction zone, since it was very high for selected experimental examples. As values of the temperature are limited, a possible explanation pointed to the conclusion that specific heat of wear products is very high **[L. 2]**. The great value of specific heat in the process of material dispersion may be explicated by analogy to the phase transition of melting, where specific heat of a substance tends to infinity. In the circumstances, the absorption of friction heat is not associated with a distinct growth in the temperature of emerging particles. Such an interpretation is also supported by the recently discovered, "cooling effect" that accompanies the friction and wear of solids **[L. 3]**. Unconventional properties of matter that accompany tribological wear have been explained with the "magma–plasma model," inter alia **[L. 4]**. The resultant great values of the systemic quantity, C, demonstrated the need to modify the original thermal balance **[L. 1]**, which has been undertaken in **[L. 2]**. Distinction between the specific heat of the wear product material, c_p', and the specific heat of the initial material, c_p, is a new component of this equation. c_p was not found to affect stationary energetic changes in a friction contact, whereas c_p' reaches $10^5 - 10^6$ J/gK. This implies the state of wear product material at the time of its generation is highly disorderly, which is a possible consequence of an intense generation of its structural defects, among other causes.

The specific heat c_p' in **[L. 2]** is a function of two systemic magnitudes, C and D, and of specific work of mechanical dissipation, a_{dyss}. D is a certain theoretical temperature above the flash temperature Θ_o, equal to a_{dyss}/c_p' **[L. 2]**, while a_{dyss} is purely mechanical energy (without heat properties) required to break up a unit of mass of a friction couple element **[L. 5]**. Importantly, C and D can be assessed in quantitative terms by means of relatively simple tribological testing, providing that the stationary temperature is recorded at a minimum, at a known distance from a friction contact. The procedure of determining their values is introduced in **[L. 2]**. Its application helped to avoid the use of a calorimeter, which is usually necessary for a quantitative description of the energy balance of friction and wear processes. However, the omission of calorimetric testing somewhat reduces the range of c_p' values analysed, i.e., an order of its magnitude and its minimum value can be estimated as C/D.

An attempt is made in this paper to express the specific heat of wear product material generated, c_p', as a function of friction process parameters, the physical properties of a material subject to wear, and some characteristics of a tribological system. This discussion is intended to arrive at a maximum c_p' for specific conditions of friction and wear and to determine a range of its variability.

The continued research into values of c_p' is also stimulated by the discussion of microscopic properties of matter in the process of fragmentation **[L. 6, 7]**.

ENERGY AND MASS BALANCE CHARACTERISING FRICTION AND WEAR OF SOLIDS – MICROSCOPIC AND MACROSCOPIC MODELS

In a microscopic model of a frictional heat source, key roles are played by both maximum temperature of instantaneous contacts of surface asperities Θ_o (the "flash temperature") and the temperature of the surface itself in the immediate vicinity, Θ. The model energy dissipation and wear is restricted to Solid 1 in the following discussion. Figure 1a shows a schematic contact between asperities of Solids 1 and 2, where the above-mentioned temperatures and elementary masses are distinguished as follows: m_{oi} – mass filling an elementary area of energy dissipation, and m_i – mass of a wear particle separated in effect of friction. In addition, the specific heat of the material within the area of energy dissipation is designated as c_p, and the specific heat of material of an emerging wear particle is marked c_p'. Figure 1b is a schematic illustration of another phase of asperity friction where the separated particle moves away from the contact. In parallel, another portion of matter, approximately equal to the mass of the separated particle m_i, characterised by specific heat c_p and temperature Θ, enters the dissipation area.

As the number of instantaneous microscopic contacts on the nominal friction surface is very high and the duration of each very short (of the order of 10^{-5} s), the heating of a macroscopic body – given fixed friction parameters – is observed as a stationary process **(Fig. 1c)**. After a specific time of the friction process, mass m of wear products will separate and mass m_o will travel through the energy dissipation area of temperature Θ_o. m_o = const is part of the model, therefore, wear m is associated with the addition of mass m at Θ and specific heat c_p to the dissipation area. The process of supplementing the mass of the energy dissipation area is designated with a schematic arrow in **Fig. 1c**.

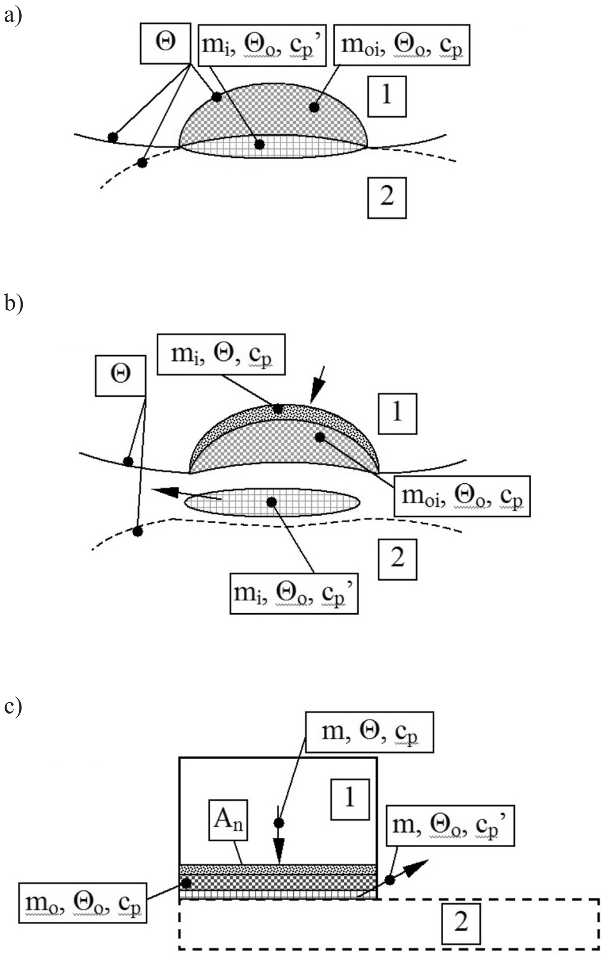

Fig. 1. Microscopic model of friction and wear processes: a) – instantaneous contact of asperities of Solids 1 and 2, with the area of energy dissipation and a future wear particle marked, b) instant of wear particle separation and a new material portion entering the dissipation area, c) macroscopic effect of the wear process at the microscopic level

Rys. 1. Model mikroskopowy procesu tarcia i zużywania: a) chwilowy styk nierówności powierzchni ciał 1 i 2 z zaznaczeniem obszaru dyssypacji energii i przyszłej cząstki zużycia, b) moment oddzielania cząstki zużycia i przechodzenie do obszaru dyssypacji nowej porcji materiału, c) makroskopowy skutek procesu zużywania zachodzącego na poziomie mikroskopowym

Mechanical energy supplied to the system, equal to work of friction $A_{t1\text{-}2}$, dissipates within the system producing dissipation heat Q_{dyss} and the work of mechanical dissipation A_{dyss}. The dissipation heat triggers thermal processes in the system and the work of mechanical dissipation causes tribological wear **[L. 8–9]**:

$$A_{t1\text{-}2} = Q_{dyss} + A_{dyss} \tag{1}$$

On consideration of the physical magnitudes shown in Figure 1c, the quantity of friction heat can be described as follows:

$$Q_{dyss} = m_o c_p(\Theta_o - \Theta) + mc_p'(\Theta_o - \Theta) \tag{2}$$

In a special case of zero wear, friction heat Q_{dyss} equals the work of friction $A_{t1\text{-}2}$ and Θ = 0 **[L. 1]**. Thus, m_o involved in the process of energy dissipation will be described by the following:

$$m_o = \frac{A_{t1-2}}{c_p \Theta_o} \tag{3}$$

Since the work of mechanical dissipation A_{dyss} is an $\eta<1$ part of friction's work, $A_{dyss} = \eta A_{t1\text{-}2}$, and the latter is also expressed as a product of specific work of wear e_R^x times a worn mass m, then

$$A_{dyss} = m\eta\, e_R^x = ma_{dyss} \tag{4}$$

where $a_{dyss} = \eta\, e_R^x$ is specific work of mechanical dissipation **[L. 5]**.

Equation (4) must be supplemented as it contains an unknown value of η. I suggest the following formula, developed by J. Sadowski **[L. 5]**, to describe the missing parameter:

$$\eta = k\frac{H}{p} \tag{5}$$

where p – nominal unit pressure, H – material hardness, and k – wear coefficient.

The specific work of wear can be expressed using J.F. Archard's equation as a function of material hardness, friction coefficient, and k. Since the volume of worn material V is described by

$$V = k\frac{lN}{H} \tag{6}$$

where l – path of friction and N – normal pressure, the mass of worn material can be described by the following relations:

$$m = k\frac{\rho l N}{H} = k\frac{\rho A_{t1-2}}{\mu H} \tag{7}$$

hence,

$$e_R^x = \frac{A_{t1-2}}{m} = \frac{\mu H}{\rho k} \tag{8}$$

where ρ – density of worn material.

The thermal balance (2) in consideration of (3) can be formulated as follows:

$$Q_{dyss} = \frac{A_{t1-2}}{\Theta_o}(\Theta_o - \Theta) + mc_p'(\Theta_o - \Theta) \qquad (9)$$

It implies a quantity of friction heat Q_{dyss} is determined by the work of wear A_{t1-2}, the temperatures Θ_o and Θ, specific heat c_p', and the mass m of emerging wear products. On the other hand, specific heat of worn material c_p is not an actual part of the thermal balance characterising the stationary process, although it was initially introduced into Equation (2).

SPECIFIC HEAT OF GENERATED PRODUCTS OF TRIBOLOGICAL WEAR – ENERGETIC ANALYSIS

The balance of energy dissipated in a stationary tribological process (1) on consideration of (2–4) becomes:

$$e_R^x \frac{\Theta}{\Theta_o} = c_p'(\Theta_o - \Theta) + a_{dyss} \qquad (10)$$

Specific heat c_p' results from the foregoing equation:

$$c_p' = \left(e_R^x \frac{\Theta}{\Theta_o} - a_{dyss}\right)\frac{1}{\Theta_o - \Theta} \qquad (11)$$

Since $c_p' > 0$,

$$e_R^x > \frac{\Theta_o}{\Theta} a_{dyss} \qquad (12)$$

and

$$\frac{\Theta}{\Theta_o} > \eta \qquad (13)$$

The introduction of η to (11) changes its form to

$$c_p' = e_R^x \left(\frac{\Theta}{\Theta_o} - \eta\right)\frac{1}{\Theta_o - \Theta} \qquad (14)$$

where η is always positive; therefore,

$$\eta = \frac{\Theta}{\Theta_o} - \frac{c_p'}{e_R^x}(\Theta_o - \Theta) \geq 0 \qquad (15)$$

The above inequality restricts values of c_p'

$$\frac{e_R^x \Theta}{\Theta_o(\Theta_o - \Theta)} = c_{p\,max}' \geq c_p' \qquad (16)$$

The foregoing discussion can be supplemented with an analysis of c_p' from **[L. 2]** using the system quantities C and D, whose values result from:

$$C = \frac{e_{R1}^x \Theta_1 - e_{R2}^x \Theta_2}{\Theta_2 - \Theta_1}, \text{ and} \qquad (17)$$

$$D = \frac{\Theta_1 \Theta_2 (e_{R1}^x - e_{R2}^x)}{e_{R1}^x \Theta_1 - e_{R2}^x \Theta_2} \qquad (18)$$

where e_{R1}^x, e_{R2}^x – specific works of wear, determined at contact temperatures Θ_1 and Θ_2, respectively.

C, expressed in J/g, is a maximum unit heat in a system, since it refers to a maximum range of temperature variation in the same system. It is described as a product of Θ_o times c_p'

$$C = c_p'\Theta_o \qquad (19)$$

On the other hand, D, expressed in Kelvin is a certain theoretical temperature exceeding Θ_o by a_{dyss}/c_p' **[L. 2]**.

$$D = \frac{a_{dyss}}{c_p'} + \Theta_o \qquad (20)$$

Published research **[L. 2]** has demonstrated the relation of C/D approximates a minimum value of specific heat c_{pmin}'. The proposed addition allows for comparing results of c_{pmin}' calculations based on (17) and (18) with the results of c_p' calculations based on (11). This is reasonable, since C and D are determined for a certain range of Θ; whereas, (11) describes the specific heat of wear products generated by a single selected value of Θ.

A QUANTITATIVE EVALUATION OF SPECIFIC HEAT OF TRIBOLOGICAL WEAR PRODUCTS

For the purposes of a quantitative description of the proposed model of stationary thermal processes accompanying the friction and wear of solids, experimental results from **[L. 10]**, employing the required thermodynamic parameters, have been used. That study has proven of use to the present analysis, since it contained information about Θ. What is more, the temperature was treated as an independent parameter of the friction process. Its value was set and stabilised by means of a heat exchanger. Temperature is normally a resultant value which is not tested, making such research of no use to this discussion. A pin-on-disk friction couple was tested. A 145Cr6 steel ring of outside diameter 121 mm, inside diameter 104 mm, and thickness 1.5 mm was the larger element. The hardness of 145Cr6 steel was 6970 MPa. The smaller element – a 5 x 5 x 0.5 mm pin (the friction surface of 5 x 5 mm^2) – fixed in a special copper holder worked with the ring.

Eight elements of this type were used. They were made of the following: Armco iron (ferrite), C45 steel (ferrite + pearlite), C80U steel (pearlite), copper, aluminium, zinc, plumb, and LC60 (Sn+Pb) alloy. Θ at the time of friction could be set at a desirable level by means of a thermostat positioned 0.4–0.5 mm away from the friction surface on the pin side. An iron/constantan thermocouple was used to test the temperature. The relatively small dimensions of the nominal contact surface of the solids in friction, A_n, make practicable evaluations of mean Θ of the surface in line with the adopted model of thermal processes described by (9) and illustrated in **Fig. 1c**. The mass wear of the pin after the friction couple had ground in was measured with analytical scales. To illustrate the method of evaluating c_p' proposed here, selected results of tribological studies from **[L. 10]** were used, supplemented with information on some physical properties of the pin–specimen materials – **Table 1**. Values of e^x_{R1}, e^x_{R2} and e^x_{R3} were determined at Θ_1, Θ_2 and Θ_3, respectively, to discover the impact of the temperature on values of c_p'. The hardness of the tested materials, H, was far lower than that of the ring material; therefore, its wear has been ignored in this analysis (as per the model – **Fig. 1**). **Table 2** lists wear coefficients k_1, k_2, and k_3 (Eq. 8), parameters η_1, η_2, and η_1 (Eq. 5), and the unit work of mechanical dissipation, a_{dyss} (Eq. 4), determined on the basis of data from **Table 1**. **Table 3** shows the calculated values of the system quantities C and D based on (17) and (18) and minimum values of c_{pmin}', i.e. relations of C/D. **Table 4** provides the specific heat of wear products (c_{p1}', c_{p2}', and c_{p3}') calculated according to (11) and their corresponding flash temperatures (Θ_{o1}, Θ_{o2}, and Θ_{o3}) derived from (19), specific heat ($c_{p1}{'}_{max}$, $c_{p2}{'}_{max}$, and $c_{p3}{'}_{max}$) computed as per (16) and temperature differences (D_1 - Θ_{o1}, D_2 - Θ_{02}, and D_3 - Θ_{03}).

Table 1. Specific work of wear, e^x_{R1}, e^x_{R2} and e^x_{R3}, at Θ_1, Θ_2, Θ_3, unit pressures p, friction coefficient μ and velocity v = 1 m/s for dry friction of eight metal specimens with hardness H following the tests described in [L. 10]

Tabela 1. Praca właściwa zużycia e^x_{R1}, e^x_{R2} i e^x_{R3} wyznaczona przy temperaturach Θ_1, Θ_2, Θ_3, naciskach jednostkowych p, współczynniku tarcia μ i prędkości v = 1 m/s dla przypadków tarcia suchego ośmiu różnych próbek metali o twardości H według badań opisanych w publikacji **[L. 10]**

Material	μ	ρ kg/m^3	H MPa	p MPa	Θ_1 K	e^x_{R1} MJ/g	Θ_2 K	e^x_{R2} MJ/g	Θ_3 K	e^x_{R3} MJ/g
Fe	0.6	7860	1746.18	0.785	298	26.76	313	5.443	333	3.38
C45	0.6	7860	2158.2	1.177	298	62.41	313	15.692	333	9.08
C80U	0.6	7860	2687.94	1.177	298	6.74	313	3.095	333	1.24
Cu	0.51	9830	1236.06	0.392	293	14.51	313	11.84	333	6.61
Al	0.43	2700	794.61	0.392	293	19.26	313	11.108	333	8.44
Zn	0.5	7130	431.64	0.392	293	12.19	313	4.676	333	4.03
Pb	0.8	11340	58.86	0.020	293	0.79	303	0.635	313	0.43
LC60	0.5	8500	78.48	0.078	293	2.39	303	1.341	313	0.94

Table 2. Wear coefficients k_1, k_2, k_3, parameters η_1, η_2, η_1, and unit work of mechanical dissipation a_{dyss}, based on the figures in Table 1

Tabela 2. Wyznaczone w oparciu o dane w **Tabeli 1** współczynniki zużywania k_1, k_2, k_3, parametry η_1, η_2, η_1 i praca jednostkowa dyssypacji mechanicznej a_{dyss}

Material	k_1	η_1	k_2	η_2	k_3	η_3	a_{dyss} MJ/g
Fe	4.98E-06	0.0111	2.449E-05	0.0545	3.944E-05	0.0877	0.2965
C45	2.64E-06	0.0048	1.050E-05	0.0193	1.814E-05	0.0333	0.3021
C80U	3.04E-05	0.0695	6.630E-05	0.1514	1.655E-04	0.3779	0.4686
Cu	4.42E-06	0.0139	5.416E-06	0.0171	9.702E-06	0.0306	0.2022
Al.	6.57E-06	0.0133	1.139E-05	0.0231	1.499E-05	0.0304	0.2565
Zn	2.48E-06	0.0027	6.473E-06	0.0071	7.511E-06	0.0083	0.0333
Pb	5.26E-06	0.0155	6.539E-06	0.0192	9.657E-06	0.0284	0.0122
LC60	1.93E-06	0.0019	3.443E-06	0.0035	4.911E-06	0.0049	0.0046

Table 3. C and D for the test results in Table 2 and minimum values of c_{pmin}'= C/D

Tabela 3. Wyznaczone wielkości systemowe C i D dla przypadku wyników badań zamieszczonych w **Tabeli 2** oraz wartości minimalne ciepła właściwego c_{pmin}'= C/D

Material	C_1 MJ/g	D_1 K	C_1/D_1 ($c_{p1\ min}$') MJ/gK	C_2 MJ/g	D_2 K	C_2/D_2 ($c_{p2\ min}$') MJ/gK	C_3 MJ/g	D_3 K	C_3/D_3 ($c_{p3\ min}$') MJ/gK
Fe	418.055	317.075	1.31847	28.906	371.938	0.07772	195.684	338.752	0.57766
C45	912.439	318.383	2.86585	94.398	365.031	0.25860	444.987	339.795	1.30957
C80U	69.319	326.975	0.21200	27.791	347.858	0.07989	45.589	342.058	0.13328
Cu	27.276	448.870	0.06076	75.240	362.255	0.20770	51.258	375.943	0.13634
Al.	108.319	345.098	0.31388	33.314	417.364	0.07982	70.817	372.687	0.19002
Zn	105.404	326.885	0.32245	6.080	553.726	0.01098	55.742	357.075	0.15611
Pb	3.907	352.253	0.01109	5.782	336.279	0.01719	4.844	340.785	0.01421
LC60	29.395	316.823	0.09278	11.210	339.246	0.03304	20.303	327.492	0.06199

Table 4. Specific heat of wear products: c_{p1}', c_{p2}', c_{p3}' at: Θ_{o1}, Θ_{o2}, Θ_{o3}, respectively; c_{p1}'$_{max}$, c_{p2}'$_{max}$, c_{p3}'$_{max}$ and temperature differences $D_1 - \Theta_{o1}$, $D_2 - \Theta_{02}$, $D_3 - \Theta_{03}$

Tabela 4. Wartości ciepła właściwego powstających produktów zużycia: c_{p1}', c_{p2}', c_{p3}' przy temperaturach odpowiednio: Θ_{o1}, Θ_{o2}, Θ_{o3}; ciepła właściwego c_{p1}'$_{max}$, c_{p2}'$_{max}$, c_{p3}'$_{max}$ oraz różnice temperatur $D_1 - \Theta_{o1}$, $D_2 - \Theta_{02}$, $D_3 - \Theta_{03}$

Material	$c_{p1\ max}$' MJ/gK	c_{p1}' MJ/gK	Θ_{o1} K	$c_{p2\ max}$' MJ/gK	c_{p2}' MJ/gK	Θ_{o2} K	$c_{p3\ max}$' MJ/gK	c_{p3}' MJ/gK	Θ_{o3} K	$D_1 - \Theta_{o1}$ K	$D_2 - \Theta_{02}$ K	$D_3 - \Theta_{03}$ K
Fe	1.33514	1.31941	316.85	0.08389	0.07851	368.16	0.63513	0.57854	338.24	0.22	3.78	0.51
C45	2.88170	2.86680	318.28	0.26537	0.25943	363.87	1.35648	1.31046	339.56	0.11	1.16	0.23
C80U	0.23093	0.21343	324.78	0.09735	0.08124	342.09	0.21866	0.13465	338.58	2.20	5.77	3.48
Cu	0.06254	0.06122	445.57	0.21244	0.20826	361.28	0.14176	0.13688	374.47	3.30	0.97	1.48
Al.	0.31962	0.31462	344.28	0.08297	0.08044	414.17	0.19739	0.19070	371.34	0.82	3.19	1.35
Zn	0.32354	0.32255	326.78	0.01118	0.01104	550.71	0.15760	0.15620	356.86	0.10	3.02	0.21
Pb	0.01133	0.01112	351.15	0.01760	0.01723	335.57	0.01470	0.01425	339.93	1.10	0.71	0.86
LC60	0.09299	0.09279	316.77	0.03319	0.03306	339.11	0.06233	0.06201	327.42	0.05	0.14	0.07

CONCLUSIONS

The values of the specific heat of wear products c_p', found in **[L. 2]** to range 10^5- 10^6 J/gK, have inspired further analysis to potentially affirm the results. The procedure of evaluating this physical magnitude proposed in **[L. 2]** based on two system quantities, C and D, computed for a selected range of temperature Θ. The quotient C/D, on the other hand, is but an approximation to the minimum c_p'. Another way of determining the specific heat of wear products is postulated here. The analyses started from the thermal balance equation describing the stationary process of tribological wear (2). Both the specific heat of the material involved in the process, c_p, and of wear products' material, c_p', have been distinguished. The continuing discussion led to an important conclusion, namely, that c_p has no effect on thermal processes associated with friction and wear. It can be explained by absence of the material's specific heat in descriptions of stationary conduction, where Fourier law is applied. The appearance of c_p' in Equations (2) and (9), on the other hand, arises from non-stationary processes taking place in the environment of instantaneous contacts between asperities on surfaces of solids in friction. Specific heat is always present in descriptions of these processes. Another conclusion derived from (9) is that there is no direct relation between the specific heats c_p and c_p'.

The distinction between the procedures described in **[L. 2]** and this novel method of estimating c_p' for a specific, chosen value of Θ is presented in Equations (11) and (14). This value depends on wear resistance, or specific work of wear, e_R^x, temperatures Θ and Θ_o, and the structure of the energy balance, which is expressed by the parameter η, the relation of a_{dyss}/e_R^x. In addition, the determination of a theoretically possible maximum value of c_p' has been proposed in (16). The upper theoretical boundary of c_p' has been determined on the assumption η may be greater than or equal to zero. It is conditioned by e_R^x and Θ, and Θ_o.

Based on the calculation results of c_p', C and D, and the maximum temperature Θ_o, listed in Tables 3 and 4, the following statements can be made:

- In the case of each material tested at three different temperatures Θ, the specific heat of wear products, c_p', derived from (11) is greater than the minimum specific heat defined as C/D, that is, $c_p' > c_{p\ min}'$.
- Values of c_p' and $c_{p\ min}'$ differ slightly from one another.
- Temperature differences D - Θ_o are within the range 0.05 – 5.77 K, which allows for estimating Θ_o on the basis of the calculated temperature D.
- Maximum specific heat $c_{p\ max}'$ resulting from (16) is a little greater than c_p'.
- The temperature of a friction contact, Θ, has no clear effect on c_p'.
- Specific heat of wear products, c_p', determined for specific friction parameters, is within the range 0.01 – 2.87 MJ/gK, i.e. is 10^{5}- 10^{6} times greater than specific heat of a material under friction, c_p.

LIST OF KEY NOMENCLATURE

A_n – nominal friction surface [m^2],
A_{dyss} – work of mechanical dissipation [J],
$A_{t1\text{-}2}$ – work of friction along path l [J],
a_{dyss} – specific work of mechanical dissipation [J/g],
C – constant of tribological system [J/g],
c_p – specific heat of specimen material [J/g·K],
c_p' – specific heat of wear product material [J/g·K],
D – constant of tribological system [K],
e_R^x – specific work of wear [J/g],
k – coefficient of wear after J.F. Archard,
l – path of friction [m],
m – mass wear along path l [g],
m_{oi} – mass filling elementary area of energy dissipation,
m_i – mass of wear particle separated by friction,
m_o – mass of friction zone [g],
N – normal pressure against nominal surface [N],
p – unit pressure [Pa],
Q_{dyss} – heat of dissipation [J],
t – time [s],
V – volumetric wear [m^2],
v – relative sliding velocity of tribological system elements [m/s],
η – work of mechanical dissipation divided by work of wear,
ρ – material density [kg/m^3],
Θ – temperature of a solid in the environment of energy dissipation zone [K],
Θ_o – temperature of energy dissipation zone [K],
μ – coefficient of friction.

REFERENCES

1. Maciąg M.: "Thermodynamic Model of the Metallic Friction Process", ASME J. Tribol., 132(3), 2010, pp. 1–7.
2. Maciąg M.: "Specific Heat of Tribological War Debris Material", ASME J. Tribol., 137(3), 2015, pp. 1–6.
3. Sadowski J.: "Cooling Effeckt in Tribological Wear", Tribologie und Schmierungstechnik, 4, 2014, pp. 57–63.
4. Thissen P.A., Meyer K., Heinicke G.: Fundamentals of Tribochemistry, Akademie-Verlag, Berlin, 1967, p. 194.
5. Sadowski J.: "On Balancing Energy in the Friction Process of Solids Bodies", Tribologie und Schmierungstechnik, 6, 2009, pp. 27–31. 469.
6. Abdel-Aal H.A.: Discussion: "Specific Heat of Tribological Wear Debris Material" (Maciąg, M., 2015, ASME J. Tribol., 137(3), p. 031601. ASME J. Tribol., 138(1), 2016, p. 016001-1.
7. Maciąg M.: Closure to "Discussion of 'Specific Heat of Tribological Wear Debris Material", ASME J. Tribol., 138(1), 2016, p. 016001-1.
8. Sadowski J.: "Thermodynamic Theory of Friction and Wear", Tribologie und Schmierungstechnik, 6, 2002, pp. 41–47. 467.
9. Sadowski, J.: "Friction and Wear a Cause and Effect of Energy Dissipation", Tribologie und Schmierungstechnik, 1, 2011, pp. 27–41. 468.
10. Sadowski, J., Żurowski, W.: "Thermodynamic Aspects of Metals' Wear-Resistance", Tribologie und Schmierungstechnik, 3, 1992, pp. 152–159.