Investigation of the Slipping Wear based on the Rate of Entropy Generation

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Abstract
Wear is a complicated phenomenon caused by the relative movement of two contacting surfaces compressed together by a normal force. Prediction of the wear, in most cases, requires various experiments and microstructural characterization of the contacting surfaces. Mathematical models based on physical concepts could provide considerable help in understanding the physical behavior and hence the prediction of this phenomenon. Considering the importance of the generated heat in wear, it seems that thermodynamic parameters are suitable measures for wear modeling proposals. One of these thermodynamic parameters is entropy, the rate of generation of which is mathematically modeled for the sliding wear in this work. For this purpose, experimental wear data from two different materials, namely, Steel 4140 and 70-30 Brass were also considered. The results showed a direct relation between the wear depth of 70-30 Brass and the generated entropy. Moreover, a linear relationship was observed between a number of parameter pairs such as 70-30 Brass temperature – rate of entropy generation, wear depth – transferred heat to 70-30 Brass, wear depth – dissipated energy, and rate of entropy generation – dissipated energy. The wear rate also showed a linear relationship with the 70-30 Brass temperature and the rate of entropy generation. The linearity of the "wear depth – rate of entropy generation" suggests the rate of entropy generation as a decent criterion for the prediction and design of the tribo-systems.

Keywords
Wear, Rate of entropy generation, Energy dissipation, Heat transfer.

1. Introduction

Tribology is the science of studying the interactions of the contacting surfaces with relative motion. In many engineering applications such as bearings, gears, seals, clutches and washers, a clear understanding of the contacting surfaces and their wearing condition can be of significant help in their designand analysis [1-3]. In general, wear mechanisms can be classified into three categories: mechanical, chemical and thermal. Moreover, seven wear modes can be realized as abrasive, adhesive, flow, fatigue, chemical (corrosive), thermal (melt) andatomic(diffusive) wear [1]. Coefficient of friction (COF), and wear resistance are not intrinsic properties of materials [4]. COFis related to the parameters affecting the contact conditions and the general environmental features. Wear and COFare considered as two response types of a tribosystem [4]. In other words, wear volume (the volume worn and removed) and COF are the responses of a tribosystem to the contact (normal load, relative velocity of the contacting surfaces, materials, roughness and so on) and environment (temperature, atmosphere, humidity, and so on) conditions, respectively.

Considering the complexity of wear mechanisms and modes on the one hand and diversity of materials candidates for different applications along with economical costs of experimental wear measurement and testing on the other hand, simulation and modeling based analysis of the wear phenomenon attracts a remarkable attention and interest. Studying the friction, wear and lubrication in the form of mathematical models composed of central physical quantities can assist the understanding of the physical conditions governing a tribosystem. Intensive work has been conducted in this direction and multiple avenues have been opened. Meng and Ludema tried to present equations for predicting the wear [5]. Siniawski et al. presented a general rule for abrasive wear [6]. Blau et al. tried to explain the wear on the basis of a friction model [7]. PõdraandAndersson tried to simulate the sliding wear using finite elements method [8]. Zmitrowicz tried to explain the rules and patterns of wear [9]. Archard proposed a general model for wear [10]. Quinn studied and explained the oxidative wear mode [11-13].

Several works have been conducted on an energy basis to model the wear and have shown a linear relationship between the dissipated energy and wear [14-18]. In the present work, it is intended to evaluate the wear phenomenon based on the entropy generation rate. Since entropy is a thermodynamic concept, exploitation of thermodynamics and heat transfer rules will be necessary. Although few attempts have been reported in this direction, due to the complicated mathematics used and the ambiguity of the physical nature proposed for wear in such works, their real applicability has been challenging. Amiri and Khonsari tried to collect and review the reports in the field of thermodynamics of friction and wear [19].

In this work, it is aimed to propose a comprehensive and practical method for calculation of the rate of entropy generation in the sliding wear and, as a case of study, the results have been used to assess the wear behaviors of AISI 4140SS and 70-30 brass. Since the entropy is a thermodynamic quantity, from a mathematical point of view, it is an exact differential. Therefore, its integral over a closed path equals zero and is a point function. In other words, its variations do not depend on the shape of the function over its path and only depend on the initial and final points of the path. From the mathematical viewpoint, independency of the entropy from the path is translated into lack of complexity in studying the wear processes and modes. Utilization of the entropy generation rate for simulation of the wear of materials provides the possibility of analysis and prediction of a tribosystem without getting involved in the active and dominant wear processes identification and their required microstructural studies.

2. Calculation of the entropy generation rate

Thefundamental equation of conduction heat transfer is:

$$c\frac{\partial T}{\partial t} = \dot{Q} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \quad (1)$$

Whereρ is the density, c is the specific heat, k is the heat conduction coefficientand $\dot{Q}$ is the volumetric heat generation rate. If k is a function of temperature only, equation 1 can be rewritten in the following form:

$$\rho c\frac{\partial T}{\partial t} = \dot{Q} + k\nabla^2 T + \frac{\partial k}{\partial T}(\Delta T)^2 \quad (2)$$

and if there is no heat source, the equation is simplified as:

$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + \frac{\partial k}{\partial T}(\Delta T)^2 \tag{3}$$

According to the second rule of thermodynamics, the volumetric entropy generation rate for a small control volume can be written as [20]:

$$\dot{S}_{gen} = \rho \frac{\partial s}{\partial t} + \nabla(\frac{q}{T}) \tag{4}$$

where q is the thermal flux and $\dot{S}_{gen}$ is the specific entropy of a unit volume. On the other hand, the thermal flux can be calculated using the following equation [20]:

$$q = -k\nabla T \tag{5}$$

By replacing the Eq.5 in Eq.4:

$$\dot{S}_{gen} = \rho \frac{\partial s}{\partial t} + \nabla(\frac{-k\nabla T}{T}) \tag{6}$$

The entropy of a solid object can be calculated in the following form [20]:

$$ds = c\frac{dT}{T} \tag{7}$$

where c is the specific heat. Using equations 3, 6, and 7, it is possible to define the rate of generation of the volumetric entropy as:

$$\dot{S}_{gen} = \frac{k}{T^2}(\nabla T)^2 \tag{8}$$

and the total entropy can be obtained via:

$$S_{gen} = \int_t \int_V \frac{k}{T^2}(\nabla T)^2 \, dV \, dt \tag{9}$$

If equations 5 and 8 are combined, the volumetric entropy generation rate can be obtained via equation 10:

$$\dot{S}_{gen} = \frac{q^2}{k.T^2} \tag{10}$$

In order to evaluate the total entropy rate in wear, one needs to calculate the entropy generation rate in both contacting materials. The share of each contact from the generated heat in the interface is shown in Fig.1.

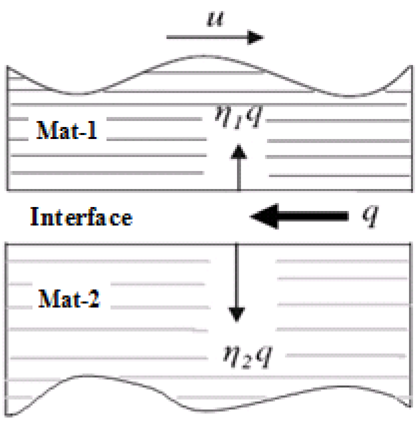

Fig.1.The generated heat in the interface of two contacts

The generated heat in the interface of two contacting materials is $q = -k\nabla T = \mu_{ave}Nu$ [3, 19, 21, 22]. μ_{ave}, N and u are the average COF, normal load and the relative velocity, respectively. The transferred fraction of the generated heat to the first material is $q_1 = \eta_1 q$ and that to the second contact material is $q_2 = \eta_2 q$. The η_1 andη_2 multipliers are calculated through equations 11 and 12, respectively [23, 24].

$$\eta_1 = \frac{\{C_{P2}k_2\rho_2\}^{\frac{1}{2}}}{\{C_{P2}k_2\rho_2\}^{\frac{1}{2}} + \{C_{P1}k_1\rho_1\}^{\frac{1}{2}}} \tag{11}$$

$$\eta_2 = 1 - \eta_1 \tag{12}$$

Where C_p is the specific heat at constant pressure.
The rate of total entropy generation is calculated via equation 13:

$$(\dot{S}_{gen})_{Tot} = \frac{q_1^2}{k_1 . T_1^2} + \frac{q_2^2}{k_2 . T_2^2} \tag{13}$$

3. Experimental results

In the present work, the results provided in Ref. [3] for the evaluation of the wear behavior of AISI 4140SS and 70-30 brass using a (LRI-1Aring-on- ringtribometer) have been used to verify the viability of the proposed method. Experimental details can be found in Ref. [3].Here, we just briefly summarize the properties of the materials used and their wear test conditions and results. Table 1 shows the physical properties of AISI 4140 SS and 70-30 brass.

Table 1. Physical properties of the wearing pair [3]

Wearing material	Thermal conductivity (W/m-K)	Specific heat constant pressure (J/kg-k)	Density (kg/m3)	Hardness (MPa)
70-30 Brass	120	375	8.53×10^3	**390.5**
Steel 4140	42.7	500	7.85×103	**2840**

Loading conditions in the wear tests are presented in Table 2.

Table 2. Loading conditions in wear experiments [3]

Wearing material	Harder material	Load (N)	Speed (m/s)
70-30 Brass	Steel 4140	13.34	**0.141**
70-30 Brass	Steel 4140	13.34	**0.282**
70-30 Brass	Steel 4140	8.89	**0.141**
70-30 Brass	Steel 4140	8.89	**0.282**

The wear results are summarized in Table 3.

Table 3. Summary of the wear results [3]

Sliding pair	Load (N)	Speed (m/s)	Steady state temperature (m/s)	Coefficient of friction (N)	Wear rate (μm/s)×10^3
Brass-Steel(4140)	13.34	0.282	32	0.46	**75.1**
Brass-Steel(4140)	13.34	0.141	30	0.55	**41.7**
Brass-Steel(4140)	8.89	0.141	29	0.56	**34.5**
Brass-Steel(4140)	8.89	0.282	30	0.49	**53.4**

4. Results and discussion

The rate of entropy generation in both AISI 4140 SS and 70-30 brass was calculated based on the wear experiments results. Evaluation of the total entropy generation rate was conducted based on the summation of the entropy generated in both materials. In the wear process, the dissipated energy originating from the work of the friction force during the entire process is responsible for materials modification and loss. This energy is mainly consumed on temperature rise of materials, generation of defects in the materials structure, bond breaking in atomic and molecular levels and finally loss of materials. In all the plots of this section R^2 is the square of the error (the distance between the experimental data and the fitted curve). In general, the closer the R^2 value to unity, the higher the accordance of the fitted curve with the real experimental results. Archard has proposed the following relation for the worn volume [10]:

$$W = K\frac{SN}{H} \tag{14}$$

WhereW is the wear volume, H is the hardness, N is the normal load, S is the wear distance, and K is the constant of proportionality. If COF is multiplied in both numerator and denominator of equation 14, equation 15 can be derived in which E is the dissipated energy due to friction force. The dissipated energy is the product of the friction force and the wear distance and therefore, the dissipated energy is the product of three parameters: COF, normal load and wear distance.

$$W = \left(\frac{K}{H\mu}\right)E \tag{15}$$

Equation 15 demonstrates a linear relationship between the wear volume and the dissipated energy. Many scholars have highlighted such linearity [15-18]. In Fig. 2 the wear depth of 70-30 brass is plotted versus the dissipated energy confirming the linear relationship of the wear with the dissipated energy.

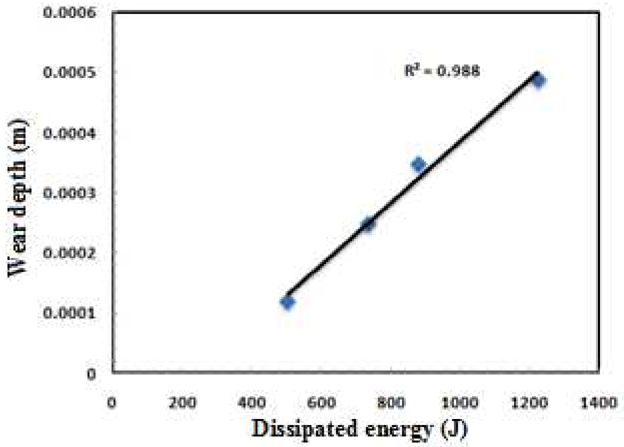

Fig. 2.Wear depth–dissipated energy plot for 70-30 brass

Fig. 3 shows the relation of the generated entropy with the dissipated energy.

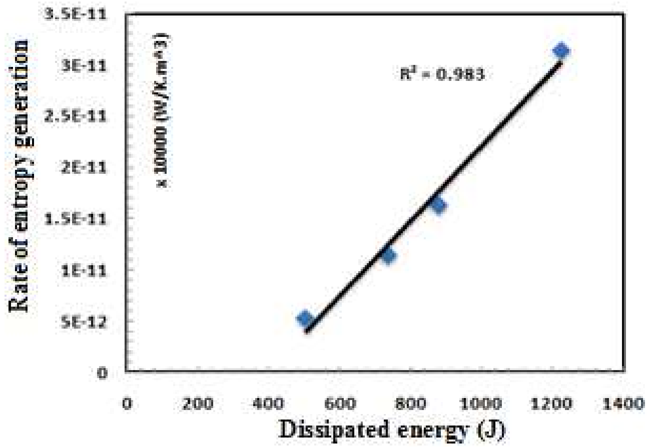

Fig.3. Generated entropy rate–dissipated energy plot

Since the generated entropy rate – dissipated energy plot is linear, it is expected that the wear volume also follows a linear relationship with the generated entropyrate. Fig. 4 shows the wear depth – generated entropy rate plot. This plot shows that the increase of the generated entropy rate leads to increase of the material wear in a linear way.

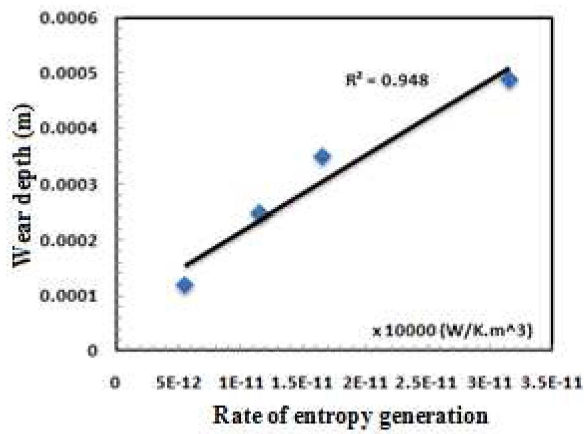

Fig. 4. Wear depth – generated entropy rate plot

A linear relationship between wear and the generated entropy rate has also been reported in other investigations [25-27]. In the current work, however, a simpler mathematics has been used and it has been tried to explain clearly the reason of using entropy, that is, it is anexact differential. Moreover, it has been attempted to demonstrate the generalizability of this linearity to other wear conditions. These results reinforce the assumption of the validity of the linear relationship between the wear and the generated entropy rate for all materials. In other words, for a given contacting pair of materials under wear conditions, as long as the wear mode does not change, the linear relationship between wear and the generated entropy rate is retained. Therefore, it is possible in this way to monitor and predict the wear behavior of a given tribosystem.

Fig. 5 shows the plot of transferred heat to AISI 4140 SS and 70-30 brass as a function of the dissipated energy. This plot represents the linear relationship between the heat transferred to the contacting materials and the dissipated energy.

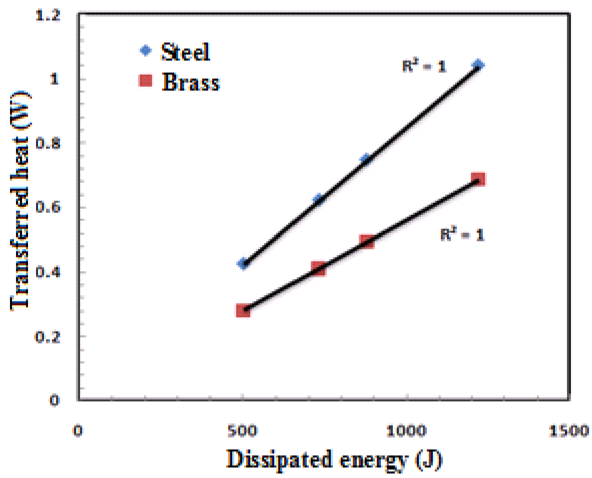

Fig.5. Transferred heat to AISI 4140 SS and 70-30 brass – dissipated energy plot

In Fig. 6 the temperature of 70-30 brass has been plotted as a function of the generated entropy rate and a linear relationship between the two is revealed.

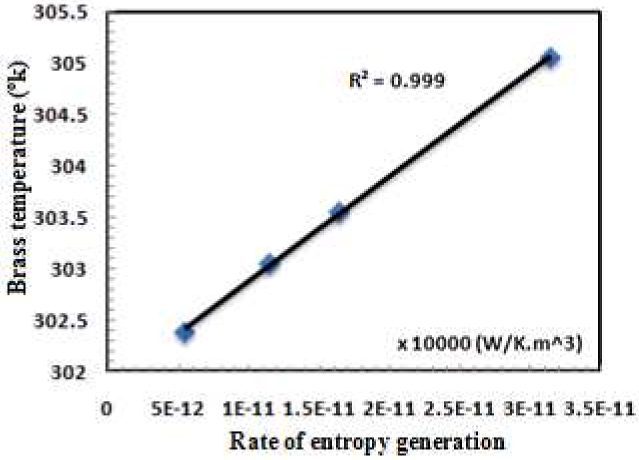

Fig. 6. Temperature of 70-30 brass – generated entropy rate plot

Fig. 7 shows the wear depth – transferred heat to 70-30 brass plot and again, the linear relationship between the two parameters is confirmed.

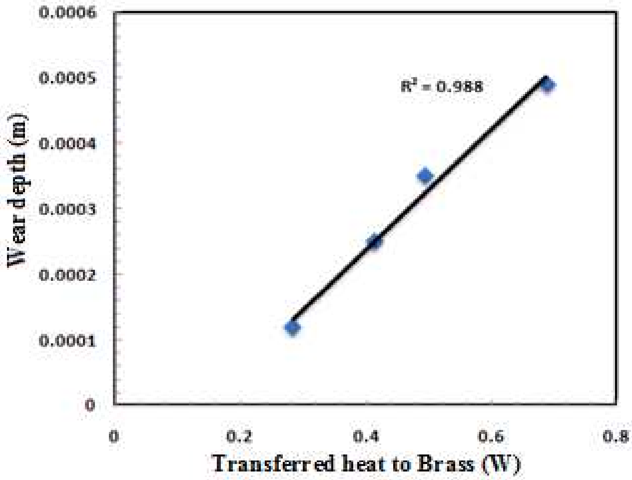

Fig. 7. Wear depth – transferred heat to 70-30 brass plot

Fig. 8 shows the temperature rise of the 70-30 brass as a function the heat transferred to it. It can be seen that the temperature rise keeps a constant rate versus the heat transferred to it.

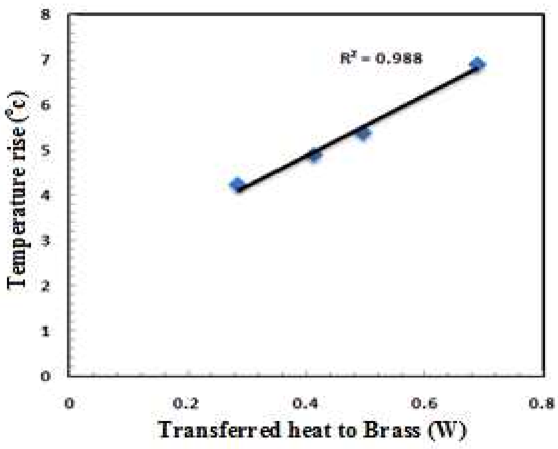

Fig. 8. Temperature rise of the 70-30 brass – the heat transferred to it

Fig. 9 shows the wear rate of 70-30 brass as a function of its temperature. Similarly, this plot reveals a linear relationship between the wear rate of 70-30 brass and its temperature.

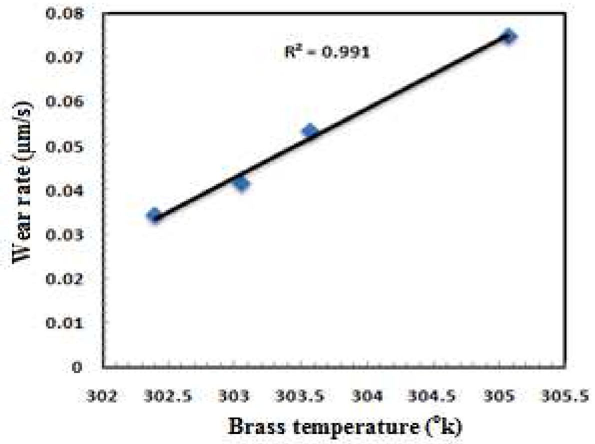

Fig. 9. Wear rate of 70-30 brass – temperature of 70-30 brass

Fig. 10 shows the wear rate as a function of the generated entropy rate. This plot confirms a linear relationship between the wear rate and the generated entropy rate.

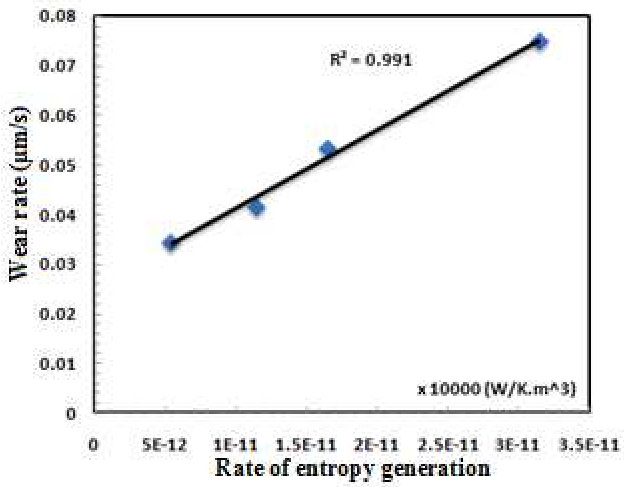

Fig. 10. Wear rate – generated entropy rate plot

The linearity of the above plots provides the opportunity of interpolation and extrapolation of various parameters in unexperienced conditions. In fact, by carrying out a limited number of wear experiments and plotting different parameters (wear volume, dissipated energy, temperature, transferred heat and wear rate) as a function of the generated entropy rate, it is possible to predict those parameters in other wear conditions.

5. Conclusion

In this work the generated entropy rate in sliding wear was mathematically modeled. The obtained relationship for the generated entropy rate is valid for reversible and irreversible processes. In addition, the manner of division of the generated heat between the two contacting materials was shown. Supporting experiments were carried out on AISI 4140 SS and 70-30 brass contact pair under sliding wear conditions. The total generated entropy rate was calculated for this case study. It was shown that the wear of 70-30 brass follows a linear relationship with the dissipated energy and the generated entropy rate. Since the wear test results were for two different normal loads and relative velocities, it is possible to assume the validity of the linear relationship of wear with the generated entropy rate also for other conditions. The temperature of 70-30 brass and its wear rate also showed linear relationshipwith the generated entropy rate. Therefore, the generated entropy rate, similar to dissipated energy, is a convenient criterion for the prediction of wear parameters such as wear volume, dissipated energy, temperature, transferred heat and wear rate. From the physical point of view, the entropy represents the extent of disorder in a system. On the other hand, wear phenomenon is a depreciatory and irreversible process and is accompanied by entropy generation (temperature rise of the mater, generation of structural defects, bond breaking in atomic and molecular levels and finally material loss). Accordingly, the entropy generation rate is a notable criterion for assessment and prediction of the wear.

6. References

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