Estimation of the tribotechnical parameters of the "piston skirt–cylinder liner" contact interface from an IC-engine for decreasing the mechanical losses

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Abstract

To decrease mechanical losses in internal combustion engines (ICE) a deeper understanding of the friction and wear processes in the main tribosystems is necessary. In particular, the interrelation between frictional energy and wear has to be analyzed. For this reason the hard to measure quantity of coefficient of accumulation of frictional energy, which is a pivotal parameter in some energy based wear theories, is determined in this work using model tribometer experiments.

The experiments are performed using small specimens made of aluminium silicon alloy and gray cast iron with a SRV tribometer (linear reciprocating motion) where loading and lubrication conditions which closely simulate the real contact situation of a piston skirt sliding against a cylinder liner near the top dead center are applied.

To calculate the coefficient of accumulation of frictional energy, experimentally gained values for the linear integral intensity of wear are analyzed numerically for various loading parameters (normal load, sliding speed, conditions of lubrication) which result in variation of the coefficient of friction and in the amount of wear.

Finally the results of the correlation between the coefficient of accumulated energy in the piston skirt–cylinder liner tribosystem and the loading conditions

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are presented. Furthermore some recommendations for technical solutions to decrease mechanical losses in the investigated system are given.
Keywords: tribosystem, contact interface, friction energy, mechanical losses.

1 Introduction

Reducing friction induced energy dissipation in wide spread tribosystems is a primary goal in economy. Especially in automotive industry the companies are trying to reduce the huge amount of tribological caused energy losses to diminish fuel consumption. In an internal combustion engine (ICE) of nowadays passenger cars for example 38-68% of the total frictional losses result from the piston assembly [1]. A detailed investigation of surface interaction processes will help in finding enhanced technical solutions with optimized design according to energy efficiency and service life.

In addition to standard parameters, characterizing the loading conditions, there is linear integral intensity of wear, which is defined as wear depth per sliding distance, to describe a tribological system, including interaction conditions like nominal pressure, sliding speed, strength, coefficient of friction, lubrication conditions, etc.

The linear integral intensity of wear can be calculated by using Finite Element Methods (FEM) and evaluated with experimental studies. Using experiments offers the opportunity to gain additional information about the fraction of energy accumulated by the surfaces, called coefficient of frictional energy accumulation, which is a key parameter in combining wear and friction theories.

The coefficient of energy accumulation and its impact on the performance of a tribosystem is currently not fully understood, but first research results show, that it is a proper parameter in tribodesign to get a rational choice of the sliding materials as well as for loading and lubrication conditions.

The effects of reduced energy consumption combined with less exhaust emissions and environmental pollution due to friction induced abrasive particles will enhance a sustainable development of modern society. Especially when taking into account that the number of motor vehicle production reached a total amount of 84 million in 2012 [2].

2 The combination of energy based and molecular-mechanical theories of friction and wear

A key parameter in energy based and molecular mechanical approaches is the friction energy density ω_{DR}, which is determined from considering the thermal and mechanical processes in the sliding contact [3]. Friction energy density can be represented by the ratio of energy being consumed for overcoming the friction force to the volume of material which is strained during the tribological process.

In the case of predominating elastic deformation, the friction energy density can be represented as:

$$\omega_{DR} = \frac{\sigma^2}{2E}. \tag{1}$$

where the stress σ is the tangential force divided by the area of the contact, which can be determined from FEM analysis of the stress-strain conditions and E – is Young's modulus.

Using the correlation between frictional energy, energy density and load volume according to G. Fleischer, one can derive the energy of elastic deformation W_d:

$$W_d = \omega_{DR} \cdot V_d, \tag{2}$$

where V_d is the deformed material volume, determined by the results of FEM analysis of the stress-strain conditions.

According to the Fleischer theory, particle separation from the contact layer takes place when the energy density reaches a critical level. If during the tribological process, energy density is less than the critical value, a part of the friction energy W_R is irreversibly accumulated in the surface layer, denoted W_{sp} and the rest W_{dis} dissipates as heat and is raising the temperature of the bodies. The balance of the mechanical energy W_M, in this case is [4, 5]:

$$W_R = W_M = W_{sp} + W_{dis}, \tag{3}$$

The accumulated friction energy is directly proportional to the total friction energy with the coefficient of proportionality, named coefficient of energy accumulation ρ_R:

$$W_{sp} = \rho_R W_R = \rho_R W_M. \tag{4}$$

Given the above statements, the ratio of energy accumulation in the contact layer can be written as:

$$\rho_R = \frac{W_{sp}}{W_R} = \frac{W_d}{W_R}. \tag{5}$$

The energy accumulated by the contact layer for several load cycles n is:

$$n W_{sp} = n W_d = n \rho_R W_R. \tag{6}$$

Wear of the contact layer starts when the critical energy level W_R^* is reached, which can be seen as the fracture energy of the material with $\sigma = \sigma_B$ (material tensile strength):

$$W_R^* = \frac{\sigma_B^2}{2E} \cdot V_R, \tag{7}$$

Fatigue phenomena of contacting materials during tribological processes occur by the change of their mechanical properties resulting in reduced tensile strength. The energy balance during fracture of the contact layer can be represented as:

$$W_R^* = W_R + n_K \cdot W_{sp}, \tag{8}$$

where n_K denotes the critical number of loading cycles.

Then the critical number of loading cycles is:

$$n_K = \frac{W_R^* - W_R}{W_{sp}}, \tag{9}$$

or considering previous statements:

$$n_K = \frac{\left(\frac{\sigma_B}{\sigma}\right)^2 \cdot W_R - W_R}{\rho_R \cdot W_R} = \frac{\left(\frac{\sigma_B}{\sigma}\right)^2 - 1}{\rho_R}. \tag{10}$$

Linear integral intensity of wear, as a link between coefficient of friction and critical energy density can be defined as follows:

$$I_h = \frac{f \cdot P_a}{\omega_{DR}^*}, \tag{11}$$

with the coefficient of friction f and the nominal pressure P_a.

Thus, receiving the expanded relation for evaluation of the linear integral intensity of wear can be done by common using the energy theory of friction and wear by G. Fleischer and molecular mechanics theory of friction and wear by I.V. Kragelskiy.

Inserting (2) and the straight forward relation $W_R = \omega_{DR} \cdot V_R$ into (5) leads to:

$$\rho_R = \frac{W_{sp}}{W_M} = \frac{V_d}{V_R}. \tag{12}$$

The critical number of loading cycles then gives:

$$n_K = \frac{\left(\frac{\sigma_B}{\sigma}\right)^2 - 1}{\rho_R} = \frac{\left[\left(\frac{\sigma_B}{\sigma}\right)^2 - 1\right] \cdot V_R}{V_d}. \tag{13}$$

The worn material volume of the contact layer is:

$$\Delta V = \frac{V_d}{n_K} = \frac{V_d^2}{\left[\left(\frac{\sigma_B}{\sigma}\right)^2 - 1\right] \cdot V_R}. \tag{14}$$

The critical energy density follows to [6]:

$$\omega_{DR}^* = \frac{W_R}{\Delta V} = \frac{W_R \cdot \left[\left(\frac{\sigma_B}{\sigma}\right)^2 - 1\right] \cdot V_R}{V_d^2}. \tag{15}$$

Linear integral intensity of wear gives:

$$I_h = \frac{f \cdot P_a}{\omega_{DR}^*} = \frac{f \cdot P_a \cdot V_d^2}{W_R \cdot \left[\left(\frac{\sigma_B}{\sigma} \right)^2 - 1 \right] \cdot V_R}. \tag{16}$$

Eq. (16) can be reduced to a more convenient form considering again that $W_R = \omega_{DR} \cdot V_R$:

$$I_h = \frac{f \cdot P_a \cdot V_d^2}{\omega_{DR} \cdot \left[\left(\frac{\sigma_B}{\sigma} \right)^2 - 1 \right] \cdot V_R^2}, \tag{17}$$

or by inserting eq. (1), one gets:

$$I_h = \frac{f \cdot P_a \cdot V_d^2}{\frac{\sigma^2}{2E} \cdot \left[\left(\frac{\sigma_B}{\sigma} \right)^2 - 1 \right] \cdot V_R^2}, \tag{18}$$

then:

$$I_h = \frac{f \cdot P_a \cdot V_d^2}{\left[\frac{\sigma_B^2}{2E} - \frac{\sigma^2}{2E} \right] \cdot V_R^2}, \tag{19}$$

and finally:

$$I_h = \frac{f \cdot P_a \cdot V_d^2}{\left[\frac{\sigma_B^2 - \sigma^2}{2E} \right] \cdot V_R^2} = \frac{f \cdot P_a}{\left[\frac{\sigma_B^2 - \sigma^2}{2E} \right]} \cdot \rho_R^2. \tag{20}$$

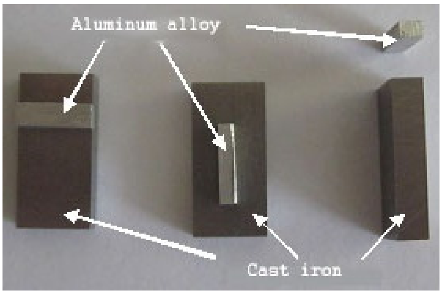
Equation (20) represents a combination of Fleischer's and Kragelskiy's approaches correlating the unknown quantity of coefficient of energy accumulation with parameters which are accessible in an enhanced experimental tribometer set up. Therefore in a first step of the experimental evaluation it is necessary to check the evolution of the coefficient of energy accumulation under varying loading conditions.

3 Laboratory equipment, prototypes, research methods and interface load conditions

For the experimental investigation test samples of piston skirt- and cylinder liner fragments from internal combustion engines (see fig. 1(a)), made of aluminium alloy and cast iron respectively, were chosen and prepared in accordance with the requirements of the imposed tribotechnical instrumentation. For sake of high reproducibility and comparability of the test results the samples were equipped with a well-defined synthetic roughness.

Specimens were tested in a tribometer (SRV 4, fig. 1(b)) providing linear oscillating relative movement. Such a tribometer platform allows analysing the impact of individual tribological parameters (oscillating frequency, stroke, and lubrication conditions) independently of each other under well-defined conditions.

The linear oscillating tribometer is equipped with sensors for friction and wear measurements with the necessary time resolution to determine the variation of the friction coefficient even within one stroke cycle. With these results it is possible to calculate the coefficient of frictional energy accumulation.

(a) 

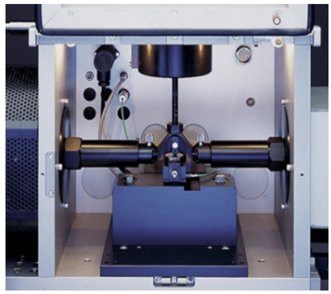
(b) 

Figure 1: Test samples of the tribometrical research (a) and SRV4-tribometer with circulation of lubricating oil (b).

A special feature of the investigated contact interface is the significant difference of the mechanical material properties for the interacting bodies (table 1).

Table 1: Mechanical properties of special cast iron and aluminium alloy.

Material	Symbol, dimension	Aluminium alloy	Special cast iron
Young's modulus	E, MPa	1.02	1.72
Poisson's ratio	ν,MPa	0.34	0.28
Hardness by Brinell	HB, –	32	184
Compressive strength limit	σ_B, MPa	190.00	294.00
Yield stress	σ_T, MPa	152.00	200.00
Mass density	ρ_{15}, kg/m^3	2725.00	7845.00

So for example cast iron has much higher values of hardness and tensile strength than the aluminium alloy. Therefore wear rates of the aluminium alloy are much higher compared to the values of the cast iron specimens. For the chosen operation conditions the wear of the cast iron was in the order of the measurement uncertainty and so it was decided to neglect the contribution of cast iron to the total wear rate and focus just on the higher values of the aluminium alloy.

Running-in phase of the interface, accompanied by a significant change in the tribotechnical parameters, was not accounted for when evaluating linear integral intensity of wear. The range of the nominal contact pressure was 1.5–7.5 MPa and the sliding speed was varied with 0.1 m/s increments from 0.1 m/s to 0.3 m/s.

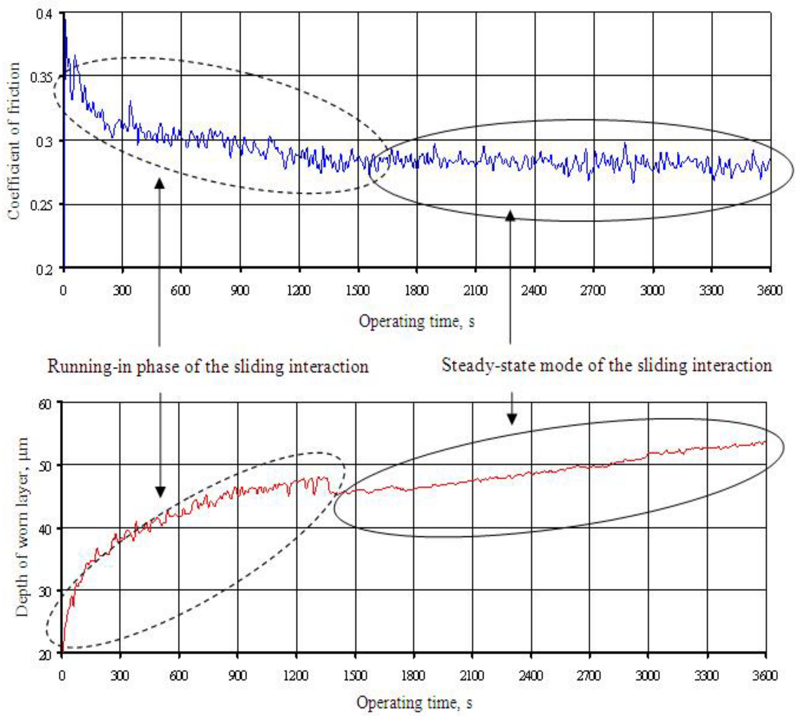


Figure 2: Dependence of the coefficient of friction (up) and the depth of worn layer (down) from the duration of the test

4 Results and discussion

Coefficient of frictional energy accumulation, as one of the hardly determinable parameters of contact interaction, is defined by a combination of theories, including molecular-mechanics (by Kragelskiy) and energy (by Fleischer) as well as by experimental data.

The analysis of the experimental results (fig. 3) revealed the correlation between height changes in the worn layer (h) and linear integral intensity of wear

(I_h) respectively, with the variation of nominal pressure (P_a) and sliding speed (V).

The nearly linear correlation of the depth of worn material with nominal pressure is in good accordance to literature about plastic deformation as well as the nonlinear behavior of linear integral intensity of wear.

The coefficient of accumulation of frictional energy for various loading conditions is represented in figure 4.

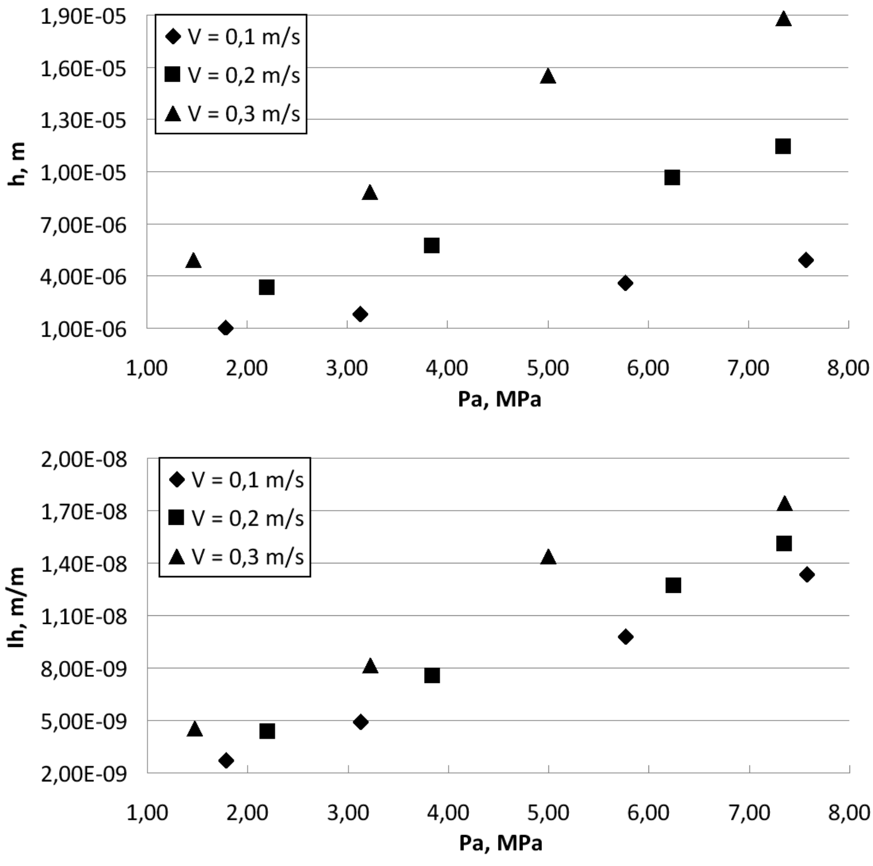


Figure 3: Correlation between the depth of the worn layer (up), and the linear integral intensity of wear (down) of the aluminium alloy sample with the nominal pressure and sliding speed.

Analyses of the experiments show that the coefficient of frictional energy accumulation stays constant during variation of nominal pressure, but for a fixed sliding velocity. Minor fluctuations in the absolute values of the coefficient of energy accumulation can be explained by temperature fluctuations of the investigated samples. The periodical lubricant supply correlates with the frequency of the temperature fluctuation and is also responsible for the variability in the values of the coefficient of friction.

Constancy of the coefficient of frictional energy accumulation for different values of nominal pressure at a fixed value of sliding speed can be explained by proportional changes in deformation component (accumulated) and thermal component (dissipated) of friction energy during the increase of nominal pressure in the contact. The increase of the absolute values of the coefficient of frictional energy accumulation during increase of sliding speed, suggests a connection between sliding speed in the interface and energy of micro-deformation in a thin surface layer of the contacting materials, as the total value of friction energy, even during increase of sliding speed, remains unchanged.

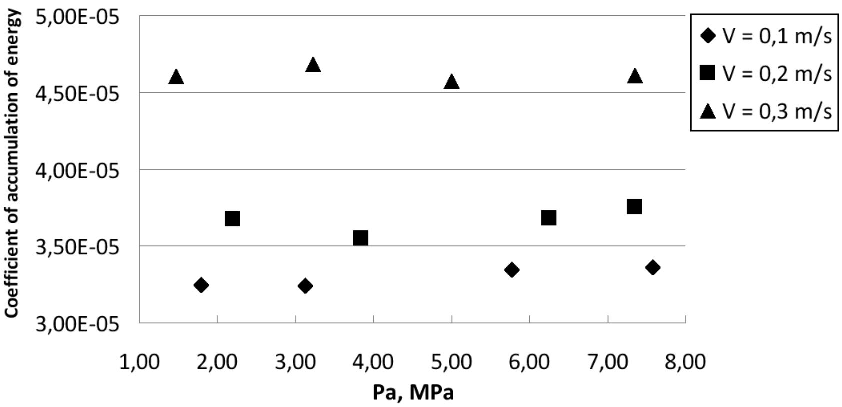


Figure 4: Correlation of the coefficient of accumulation of frictional energy with nominal pressure and sliding speed.

Energy of the micro-deformation, according to Fleischer's theory, is seen as the energy that is irreversibly accumulated in the layer before the moment of its destruction. Therefore the obtained correlations for the coefficient of accumulation of frictional energy will create the preconditions to search for the connection between the friction energy which is accumulated during contact interaction and sliding velocity. This issue still does not have the needed attention in literature, papers and proceedings of conferences, and could be the subject of a separate study.

5 Conclusions

Analysis of "aluminium alloy–special cast iron" contact interaction parameters that were used in "piston skirt–cylinder liner" interface of charged ICE, leads to the following conclusions.

1. Linear integral intensity of wear, is proportional to coefficient of friction, nominal pressure and sliding speed, respectively. In this context, a minimal

coefficient of friction would provide low wear rates. Furthermore nominal pressure in the interface should be lowered to reduce the amount of existing thermal and mechanical loads.

2. The linear integral intensity of wear shows quadratic dependence on the coefficient of accumulation of frictional energy (eq. (20)). It represents the correlation between the energy of micro-deformation and the total frictional energy during contact interaction. By reducing the coefficient of energy accumulation service life of the tribosystem could be increased. This would be possible by means of reduction of the contact temperature, increase of the dissipated part of the frictional energy and (or) by reduction of the accumulated energy of friction which is followed by deterioration of the dislocations mobility.
3. Service life of a tribocontact is directly proportional to the difference between actual compressive stresses in the contact layer and the material limits. Reducing the compressive stress is possible in two ways: reduction of the actual stress in the interface and (or) increase of the stress limit, involving the use of materials with high tensile strength values. An increase of hardness and tensile strength limit of the materials will contribute to a shift of the contact type, from plastic to elastic-plastic mode of the interaction.
4. The experimental investigation shows a variation of the coefficient of friction in the range of 0.12-0.17 for operation conditions of 1.5-7.5 MPa nominal pressure and 0.1-0.3 m/s sliding speed. The stated values of the coefficient of friction have sufficient correlation with data from literature, corresponding to “boundary” regime of lubrication, which occurs in “piston skirt – cylinder liner” interfaces of the ICE, when the piston is situated near top and bottom “dead” centers.
5. The values of linear integral intensity of wear (I_h) are found in the range of 2×10^{-9}-2×10^{-8} m/m, where highest values are connected with highest nominal pressures and sliding speeds. This fact has quite good correlation with the data from literature, for the interface “aluminium alloy – special cast iron” with different loading modes.
6. The coefficient of frictional energy accumulation (ρ_R), is independent of nominal pressure and takes the values 3.25×10^{-5}-3.27×10^{-5} for 0.1 m/s sliding speed, 3.65×10^{-5}-3.85×10^{-5} for 0.2 m/s sliding speed and 4.55×10^{-5}-4.65×10^{-5} for 0.3 m/s sliding speed. The mentioned values of the coefficient of frictional energy accumulation can be used for evaluating the service life of the interface “piston skirt – cylinder liner” in an ICE already in an early stage of design.

6 Outlook

The energy consumed for micro-deformation of the interface surface layer is considered as irreversibly accumulated energy until the destruction of the contact layer takes place. The experimental results in this paper suggest that more energy is accumulated in the surface layer if the sliding speed is increased. However, for a detailed investigation of the correlation between the coefficient of accumulation of energy and sliding speed, more experiments should be carried out.

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References

[1] K. Holmberg, P. Andersson, A. Erdemir, Global energy consumption due to friction in passenger cars, Tribology Intl (2011), doi.org/10.1016/ j.triboint.2011.11.022, 2011.
[2] OICA: http://oica.net/category/production-statistics/2012-statistics/ called on 2013-10-03.
[3] Kragelskiy I.V., Mihin N.M. Uzli trenia mashin – Spravochnik. (Tribology components of machines – Handbuch; Original: Russian). Moscow: Mashinostroenie. 1984. – 280 p.
[4] Fleischer G., Brader H., Thum H. Verschleiß und Zuverläßigkeit. Berlin: VEB, 1980. – 224 p.
[5] Fleischer G. Energetische Methode der Bestimmung des Verschleißes / Schmierungstechnik, 1973. – Band 4. – p. 9-12.
[6] Polzer G., Maißner F. Grundlagen zu Reibung und Verschleiß. Leipzig: VEB, 1983.