Estimation of the operational reliability determined with Weibull modulus based on the abrasive wear in a cylinder-piston ring system

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Methodology of research

ABSTRACT

Purpose: The main purpose of the study was to determine methodology for estimation of the operational reliability based on the statistical results of abrasive wear testing.

Design/methodology/approach: For research, a traditional tribological system, i.e. a friction pair of the AlSi17CuNiMg silumin in contact with the spheroidal graphite cast iron of EN-GJN-200 grade, was chosen. Conditions of dry friction were assumed. This system was chosen based on mechanical cooperation between the cylinder (silumin) and piston rings (spheroidal graphite cast iron) in conventional internal combustion piston engines with spark ignition.

Findings: Using material parameters of the cylinder and piston rings, nominal losses qualifying the cylinder for repair and the maximum weight losses that can be smothered were determined. Based on the theoretical number of engine revolutions to repair and stress acting on the cylinder bearing surface, the maximum distance that the motor vehicle can travel before the seizure of the cylinder occurs was calculated. These results were the basis for statistical analysis carried out with the Weibull modulus, the end result of which was the estimation of material reliability (the survival probability of tribological system) and the determination of a pre-operation warranty period of the tribological system.

Research limitations/implications: The analysis of Weibull distribution modulus will estimate the reliability of a tribological cylinder-ring system enabled the determination of an approximate theoretical time of the combustion engine failure-free running.

Originality/value: The results are valuable statistical data and methodology proposed in this paper can be used to determine a theoretical life time of the combustion engine.

Keywords: Operating reliability; Abrasive wear; Weibull modulus; Metal alloys; Statistical methods

1. Introduction

The currently operating advanced transport systems impose higher and higher requirements on the reliability of mechanical parts. Damage of interacting elements will decrease the performance, measured by the real-time operation. This includes, among others, tribological systems, which are cylinder-piston ring friction pairs operating in mechanical engines with spark ignition. The phenomena that occur on the contact surface of friction bodies are accompanied by weight loss, which directly affects the actual life of the mechanical system. This issue is very popular among the researchers involved in broadly defined materials science, as evidenced by numerous works on this subject [1-15].There are several ways to determine the wear of friction parts. One of the fundamental and widely used methods is the "pin-on-disc" method [3,4,9], which allows simulation of actual friction conditions prevailing in a cylinder-ring system. Some application found also other methods, among others, the numerical one, capable of simulating any real friction systems [5], and a relatively new method of measurement using the, so-called, replication technique [7].

This study proposes a combination of traditional methods of measurement using the "pin-on-disc" technique with statistical analysis based on the Weibull distribution [18,19]. This combination allows obtaining simultaneously the data on the wear behavior of materials, as well as the determination of pre-operation lifetime of the investigated friction pairs (cylinder-rings).

2. The aim and scope of studies

The main purpose of this study was to develop and present a methodology for estimated calculation of material reliability, based on abrasive wear behavior of AlSi17 silumin in contact with the spheroidal graphite cast iron of EN-GJN-200 grade. This tribological system was chosen as an example of abrasive friction pair operating in a traditional cylinder-piston ring system used in the automotive industry. Assuming the conditions for cylinder seizure determined by weight losses qualifying the cylinder for repair, the operational reliability of the cylinder-piston system was determined. The final outcome of the estimation of the probable failure-free operation time was the determination of a warranty period of the mechanical cylinder-piston ring system in internal combustion spark-ignition engine.

3. Materials and methods

For the research, a hypereutectic silumin, used for cylinder liners in automotive engines, was chosen; the chemical composition of the alloy is shown in Table 1.

Table 1.
Chemical composition of the AlSi17 alloy in wt.%

Alloy	Chemical composition, wt.%						
	Si	Cu	Ni	Mg	Fe	imp.	Al
AlSi17	16.42	1.33	0.02	0.11	0.14	0.02	bal.

Piston rings were made from the spheroidal graphite cast iron of EN-GJN-200 grade. The study of abrasive wear was conducted on a T01M tester, whose schematic representation is shown in Fig. 1.
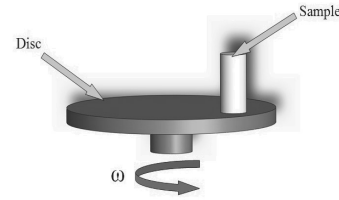

Fig. 1. Schematic diagram of device used for testing of the friction wear - T01M tester

The parameters for the measurement of friction wear were selected from the literature data [16] and are shown in Table 2. For studies, specimens with a diameter of 3 mm and a height of 18 mm were chosen. They were tested on a disc of 38 mm diameter and a height of 4 mm.

Table 2.
Friction wear test parameters [16]

Peripheral speed [m·s^{-1}]	Load [N]	Specimen surface [m^2]	Pin surface [m^2]	Pressure [MPa]	Friction path [m]
0.6	24.525	$7.07 \cdot 10^{-6}$	$87.92 \cdot 10^{-5}$	3.46	2000

To determine the tribological wear in the examined system, a comparison was made between the weight loss of pin during the test (AlSi17 silumin) and the specimen (spheroidal graphite cast iron). Based on the data obtained [16,17], the maximum wear on cylinder diameter (0.3 mm) and the volume of material available for wear were determined. Knowing the number of strokes that the cylinder bearing surface can withstand and assuming the shaft speed and an average speed of the vehicle, the theoretical number of kilometers that the motor vehicle can travel until the destruction of the cylinder occurs was determined. Under real conditions, an oil lubricant is used between the two elements, but to simplify the calculations it was assumed that the cylinder-ring system is operating in a dry friction mode.

4. Results and discussion

The results obtained during the friction wear test carried out on the AlSi17 silumin and spheroidal graphite EN-GJN-200 cast iron are given in Table 3. They provide a starting point for further calculations.

Table 3.
The results of friction wear test

Element	Weight before test [kg·10^{-3}]	Weight after test [kg·10^{-3}]	Loss of weight Δm [kg·10^{-3}]	Total loss of weight $\Sigma \Delta m$ [kg·10^{-3}]
Specimen	0.3594	0.3002	0.0592	0.2832
Disc	16.4780	16.2540	0.2240	

According to the adopted procedure, the following calculations were performed:

1) Determination of engine parameters based on own measurements and literature data [16]. Very important for calculations was the determination of a series of parameters, among which the most significant was the distance between the extreme ring planes (h1) and piston active height (H), as shown in Fig. 2.
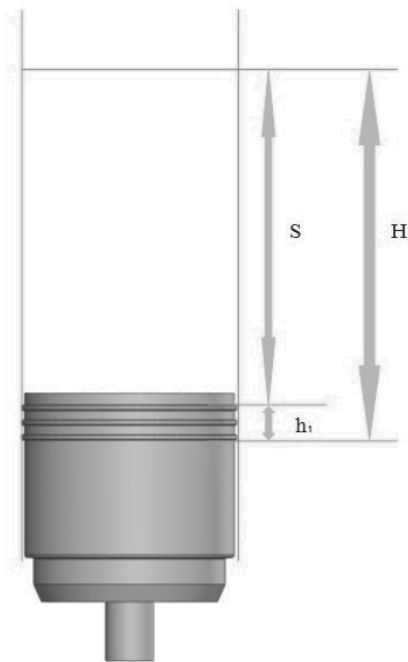

Fig. 2. Operating parameters of piston, where: S - piston stroke, H - piston active height, h_1 - distance between the extreme ring planes

All cylinder parameters necessary for calculations were measured and determined, as shown in Table 4.

Table 4.
Cylinder parameters

Parameter	Determined value
Silumin density	ρ=0.00365 [g·mm^{-2}]
Nominal diameter d_1	d_1=68 [mm]
Diameter qualifying cylinder for repair d_2	d_2=68.3 [mm]
Cylinder shape factor S/d_1	S/d_1=0.8
Piston stroke S	S=54.4 [mm]
Distance between the extreme ring planes h_1	h_1=15 [mm]
Piston active height H	H=69.4 [mm]

2) Determination of the nominal cylinder cavities qualifying for repair. This parameter was determined on the basis of [16] and its value was 0.3 mm, so the maximum diameter of the cylinder qualifying for repair is d_2 = 68.3 mm.

3) Determination of the maximum mass loss that can be smothered (Δm). According to the data given in [17], friction caused by rings affects 30% of the cylinder bearing surface (Fig. 3). To determine Δm, the data were entered into MS Excel spreadsheet. The weight loss calculated by the program was 1.772 g
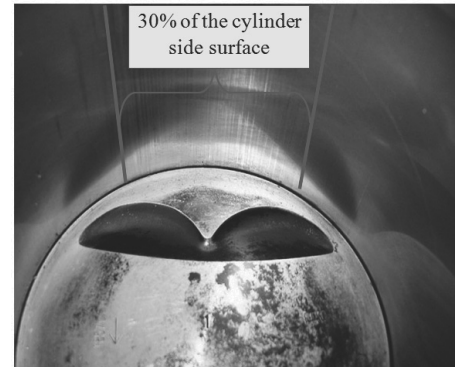
4)

Fig. 3. Photo of a damaged cylinder bearing surface

5) Determination of the theoretical number of engine revolutions to repair. The number of revolutions to seizure (n_z) was determined from equation (1):

$$n_z = \frac{S_z}{H} = 14843812 \tag{1}$$

where:
S_z - the sliding distance qualifying the cylinder liner for repair [mm],
H - the path of one stroke [mm].

6) Determination of stress acting on the cylinder bearing surface and of the "stress factor". For this purpose it was necessary to determine (based on equation 2) forces acting on the cylinder bearing surface:

$$N = \frac{Q_s}{A} \cdot \tan \beta = 6.355 \, [N] \tag{2}$$

where:
Q_s - the combustion pressure in piston chamber [Pa],
A - the face of cylinder [mm^2],
β - the angle between the piston axis and connecting rod [°].

Knowing the force acting on the cylinder bearing surface, the next step was calculation of stress acting on the cylinder bearing surface (according to Equation 3):

$$\sigma_G = \frac{N}{A_T} = 0.0142 \, [MPa] \tag{3}$$

where:
N - the force acting on the cylinder bearing surface [N],
A_T - the friction surface area [mm^2].

Comparing the stresses operating under real conditions with the stresses present during test, it was found that the test stresses were much larger than the true stresses. To properly determine the maximum distance that the vehicle can safely run, a relationship between the two stresses, known as a "stress factor" which is the true stress/test stress ratio, was determined:

$$I = \frac{\sigma_G}{\sigma_B} = 0.00409$$

(4)

where:
σ_G - the true stress acting on the cylinder bearing surface [MPa],
σ_B - the test stress [MPa].

7) Determination of the maximum distance that the vehicle can run to repair of cylinder. In the first place, the theoretical time of action (T_{DT}) and the theoretical path of action (S_{DT}), were calculated based on equations 5 and 6:

$$T_{DT} = \frac{n_z}{V_w} = 593.75 \, [min] = 9{,}85 \, [h]$$

(5)

$$S_{DT} = V \cdot T_{DT} = 689.5 \, [km]$$

(6)

where:
n_z - the number of revolutions to seizure [rev],
V_w - the shaft rotational speed [rev/min],
V - the average speed of vehicle [km/h].

Based on these results, the real time (T_{DT}) and the path (S_{TD}) were calculated allowing for the "stress factor":

$$T_D = \frac{T_{DT}}{I} = 2419.581 \, [h]$$

(7)

$$S_D = \frac{S_{DT}}{I} = 169370.76 \, [km]$$

(8)

8) The operational reliability defined by Weibull modulus [18, 19] was estimated from the following formula:

$$F(x) = 1 - \exp\left(-\frac{x}{\alpha}\right)^{\beta}$$

(9)

where:
x - the path to cylinder seizure (169 370.76 km)
α - the characteristic lifetime
β - the shape parameter

Using regression analysis and correlation, after simple transformations, factors α and β were calculated:

$\alpha = 15.552$ (10)

$\beta = 155537.36$ (11)

From the above it follows that the approximate theoretical time of the engine failure-free operation is:

$$t_G = \frac{S_D}{S_j \cdot t} = 4.6 \, [years]$$

(12)

where:
S_D - the theoretical distance to piston seizure [km],
S_j - the number of kilometers passed during one day (the assumed value is 100 km/day),
t - the number of days in a year (the assumed number is 365 days).

5. Summary and conclusions

The article presents the methodology used in calculation of the trouble-free operation of a cylinder - piston ring system, made of the AlSi17 silumin and spheroidal graphite EN-GJN-200 cast iron, respectively. The cooperation of those two elements consists in friction exerted by the ring onto the cylinder bearing surface. To determine the wear of specimens, the loss of the specimen weight during tests with well defined path of friction was compared. Maximum weight loss was determined from the data given in literature [16] referring to the maximum cylinder wear diameter (0.3 mm) and volume. The calculated mass loss Δm was 1.772 g, and it was next used in determination of the theoretical number of the cylinder strokes, knowing the theoretical number of strokes (at idle). Assuming the shaft speed of 2500 rev/min., an average speed of the vehicle (70 km/h), and taking into account the "stress factor", the theoretical number of kilometers that the vehicle can run with the tested cylinder-ring system was calculated (169 370.76 km).

At further stage of the study, based on the data taken from [17], a statistical analysis of the survival probability of a friction system based on the Weibull modulus was performed. As a result of the data implementation to MS Excel spreadsheet, two characteristic parameters α and β (Equations 9 and 10, respectively) were determined. These parameters were used to calculate the warranty period using Weibull distribution analysis, which for the investigated silumin- cast iron system was 4.6 years. It should be emphasized that because of the longest desirable lifetime of components, the determination of material reliability is currently one of the fundamental problems in modern materials science.

On the basis of own research and a series of calculations, the following conclusions have been drawn:

1. The main factor that causes the destruction of the cylinder bearing surface is a force acting perpendicular to its axis. It depends on the force of impact exerted by the mixture on the piston front face and on the angle between the cylinder axis and connecting rod.
2. To compare the results of wear tests with the wear rate in any arbitrary tribological system, it is necessary to establish the operational wear standards, maximum wear volume and mass that can be lost in wear.
3. The theoretical distance that can be traveled was estimated from the path length along which the friction pair can move,

the active height of cylinder and the average performance of a vehicle. The calculated theoretical roadworthiness was 689.5 km.

4. The performed calculations allowed for the difference in stresses occurring in both systems (true and simulated). The true-to-test stress ratio was 0.0041. Introducing this ratio to calculations increased the distance that the vehicle can safely run to 169 370.76 km.

5. The analysis of Weibull distribution modulus, used to estimate the reliability of a tribological cylinder-ring system enabled the determination of an approximate theoretical time of the combustion engine failure-free running, which was 4.6 years.

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