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The Influence of Chosen Abrasive Wear Parameters on Fault-free Operation Time of the Cylinder-Piston System

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Abstract

In the paper the method of data modeling for damages, that has values higher than zero, is being shown. With the use of Weibull distribution, with prior regression and correlation analysis, the chosen parameters, that define durability and break down level of two populations of AlSi17Cu5Mg, were set. The calculation sheet that is shown for reliability allows the creation of so called survival chart, and on the basis of durability data the average warrantee time can be defined at the pre-exploitation stage.

Keywords: Reliability, Weibull analysis, Hypereutectic Al-Si alloys, Regress and correlation analysis

1. Introduction

The desire to use newest and more durable materials, is caused mainly by increased „life-time" of the elements or decreasing their production cost. The materials that not so long ago were used only in aviation appears more and more often in the vehicles construction in automotive industry. The example of such materials are, between other, the silumins, mainly used for combustion motors construction, pistons, sleeves, hulls [1, 2]. In any of those cases, the silumin castings, due to advantageous durability and ductile properties in difficult exploitation conditions. This mainly regards the elements working in the motor compartment, where one of basic properties is durability against abrasive wear of tribological system: cylinder-piston [3,4]. It's the choice of materials that has decisive influence on wear-off of the elements during the operation, and as a consequence on definition of abrasive system durability, e.g. through calculating theoretical motor revolutions until seizure at the stage of pre-exploitation research [5÷9].

2. Scope and purpose of research

The goal of this dissertation is to present the methodology of material reliability assessment on the basis of the results from abrasive wear-off of the AlSi17Cu5Mg alloy (pin) in contact with ductile cast iron EN-GJN-200 (disc). The tribological system was chosen on the basis of an abrasive association cylinder-piston, which works in the process chamber of the combustion motor. The conditions were assumed as dry friction. In order to achieve assumed goal, the scope of research included, between the other:

- defining chosen parameters of combustion motor,
- calculating the weight decrease and motor revolutions until repair,
- defining the stress influencing the cylinder plain,

- conducting the abrasive wear-off testing,
- preparing the calculation sheet for reliability,
- regress, correlation and variance analysis,
- estimating bi-parameter Weibull distribution,
- graphic development of „survival” function chart,
- defining the theoretical warrantee time of the system.

3. Research methodology

The A390.0 alloy was used for a pin, as it is used for heavily burdened combustion motors pistons casts. The abrasive tests were done with the use of tribological tester T-01. The testing association consists fixed pin, pressed with *P* pressure force to the rotating, with certain speed, cast iron disc *n*. On the purpose of the tests, the parameters reflecting the conditions of interaction between the piston casing and the cylinder sleeve for the combustion motor were set as of 100kW power. The tests were done as per the requirement of DIN 50324 standard. The pin (ø 4×18 mm) was pressed to the abrasive plate (ø 42×3 mm), rotating at 0,55 m/s peripheral speed, with constant contact force of P=0,8 MPa. Each test was repeated 10 times. During the tests the friction force F_t was measured and recorded, and then the friction indicator μ was calculated from it. Weight decrease measurement of the interacting elements pin-disc, was done with the use of weighing scale Radwag AS220/C/2 with the accuracy of 0,1 mg. Friction distance was 2000 m.
Tribological tester T-01 is being shown in Fig. 1.

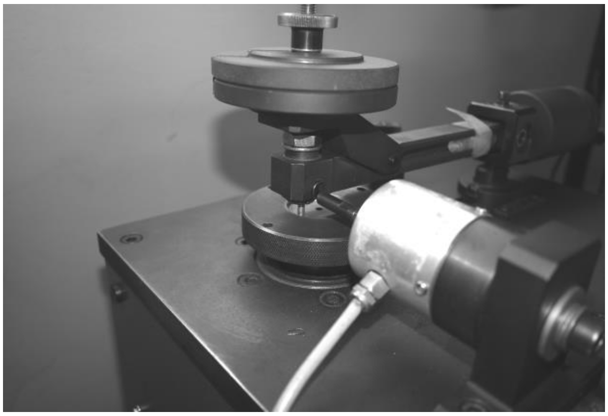

Fig. 1. Tribological T-01 tester

For further testing the following data were assumed:
d_1 – nominal diameter of the cylinder as: 68 mm,
d_2 – diameter qualifying the cylinder for the repair as: 68,3 mm,
S – piston stroke as: 54,4 mm,
w_k – cylinder shape indicator as: 0,8,
hp_U – height of sealing rings as: 2 mm,
hp_Z – height of gathering ring as: 3 mm,
h_0 – distance between the rings as: 4 mm,
h_1 – distance between outmost planes of the rings as: 15 mm,
H – active height of the piston (the height, where the rings are interacting with the plane of the cylinder, as: 69,4 mm (54,4+15 mm),
Typical sizes of standard piston are shown in Fig. 2.

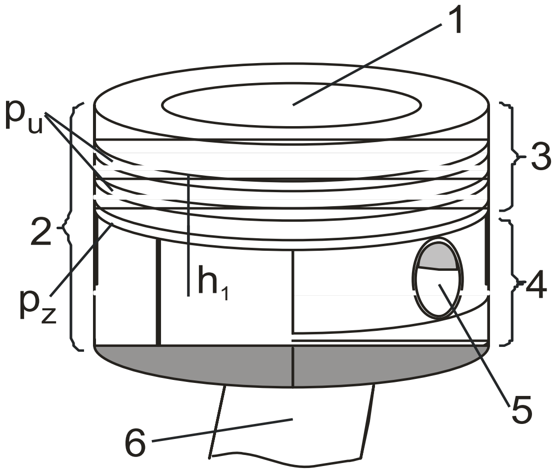

Fig. 2. General view of the piston with the most important markings
1 – bottom of the piston, 2 – casing of the piston, 3 – sealing part of the piston, 4 – leasing part of the piston, 5 – pivot hub of the piston, 6 – part of the piston’s connecting rod,

4. Research results

As per the assumed research goal, during the first stage , the actual, maximal weight, which may be grinded off from inside surface of the cylinder. In order to do it, the volume was defined, which will be grinded with decreasing diameter of the cylinder from d_1 to d_2. Multiplying calculated in this way volume with the alloy density (0,00265 $g \cdot mm^{-3}$) and assuming that friction of the rings occurs on around 30% of the cylinder plane, the possible weight decrease Δm of the cylinder plane as 1,722 g.

The result of the weight decrease testing, with dry grinding of the silumin AlSi17Cu5Mg (pin) and ductile cast iron EN-GJN-200 (disc) has been shown in Table 1.

Table 1.
Samples weight measurement (g)

Tested material	Sample weight, g		
	m_1	m_2	Δm
silumin	0,3734	0,3390	0,0344
cast iron	16,4521	16,3241	0,1280

where:
m_1 – sample’s weight before the grinding test, g,
m_2 – sample’s weight after the grinding test, g,
Δm – weight decrease, being the grinding result, g,

Next stage of the research was to define theoretical number of motor revolutions until seizure. In order to do that the following data were assumed:
l_t – friction distance as 2000 m, (from tribological testing),
l_S – friction distance of one stroke (in numbers equal to working range of the cylinder) equal to 69,4 mm.

The quotient of friction distance (l_t) to friction distance of single stroke (l_S) is the number of strokes S1, which theoretically will be implemented by the ring on the cylinder’s plane, which is

28818,5. By dividing maximal weight decrease of cylinder’s plane (Δm = 1,772 g) with silumin weight decrease (Δm = 0,034 g) it was determined, that it comes to around 51,5.

The theoretical friction distance, until the moment, when cylinder’s plane is qualified for the repair l_z=103016m, was defined by multiplying the friction distance (l_t = 2000 m) and quotient of weight decreases of cylinder’s plane and piston (51,5). Dividing it by single stroke friction distance (active height of the cylinder is 69,4mm) it was determined, that the theoretical number of revolutions until seizure n_z is around 1484382 revolutions.

Then the F_T was determined, as force, which acts on the piston as a result of an explosion of the fuel-air mix. It was assumed, that:

- burning pressure Q_S is 1400000 Pa,
- piston frontal surface A_T is 0,00363 m^2.

Dividing these two values one with the other, the F_T force is 5084,4 N.

The course of calculation in MS Excel has been shown in Fig. 3.

	P	Q	R	S	T
1	Determining the forces that are acting on the cylinder's wall				
2					
3	burning pressure in the piston's chamber (Q_S):	1400000	Pa		
4	frontal surface of the cylinder (A):	3631,68111	mm^2=	0,00363	m^2
5	Pressure acting on the piston (P_T):	5084,35355	N	$P_T = \frac{Q_S}{A}$	
6	Length of the connecting rod (k):	150	mm		
7	The lengh of the connecting arm (r):	27,2	mm		
8	Tan (β):	0,00124999		$tan\beta = \frac{r}{k^2 - r^2}$	
9	The force acting on the cylinder's plane (N):	635539521	N	$N = P_T \cdot tan\beta$	

Fig. 3. The method of determining the force acting on the cylinder’s plane

As we know, the stress is the ratio of force to plain on which the force is acting. In this case it will be the combined sum of rings height multiplied by 30% of the circle. The method of determining the stress acting on the cylinder’s plane is being shown in Fig 4.

	P	Q	R	S	T
15	Diameter of the rings (d_p)	67,9	mm		
16	combineed height of the rings (h_p):	7	mm	$h_P = 2 \cdot h_U + h_Z$	
17	side plane of the rings (A_B):	1493,19899	mm^2	$A_B = 2 \cdot \pi \cdot \frac{d_P}{2} \cdot H$	
18	cutting surface (q):	30	% of the circle		
19	friction plane (A_T):	447,959696	mm^2	$A_T = A_B \cdot q$	
20					
21					
22	stress acting on the cylinder's plane (δ_G)	0,01418743	MPa	$\sigma_G = \frac{N}{A_T}$	

Fig. 4. The method of determination of the stress acting on the cylinder’s plane

The stress indicator expresses the quotient of actual stress to the stress occurring during the tests. Since the stress occurring during the tests are bigger than actual, the actual distance, which the car equipped with piston motor will be able to travel, will also be longer than distance defined with laboratory methods. The course of calculation for stress indicator is shown in Fig. 5.

	P	Q	R	S
21				
22	stress acting on the cylinder's plane (δ_G)	0,01418743	MPa	$\sigma_G = \frac{N}{A_T}$
23	testeing stress (δ_B)	3,4689	MPa	
24	forces proportion indicator:	0,00408991		$I = \frac{\delta_G}{\delta_B}$

Fig. 5. The method of determining the stress indicator

The determination of the distance, which can be travelled by the car until the cylinder repair requires the following assumptions:

- rotary speed of the shaft V_W = 2500 rev·min^{-1},
- average velocity of the vehicle $V_{ŚR}$ = 70 km·h^{-1},
- theoretical number of revolutions until seizure n_z = 1484382.

Dividing the number of revolutions until the seizure of the piston by rotary speed of the crankshaft the theoretical time, after which the cylinder will be qualified for the repair t_n = ~ 9,85 h, and multiplying this time by average speed ($V_{ŚR}$ =70 km·h^{-1}), it would define the distance S_D as around 690 km.

The last step, to determine the time and distance of operation (t_D i S_D) is dividing the theoretical time and distance by the stress indicator, which will increase the theoretical values to the level of actual ones, including the differences between conducted laboratory tests and actual testing.

The ratio of actual distance and actual stress should be equal to the ratio of theoretical distance as per the following assertion:

$$\delta_G \cdot t_D = \delta_B \cdot t_{nT} \Rightarrow \frac{\delta_G}{\delta_B} = \frac{t_{nT}}{t_D} \Rightarrow t_D = \frac{t_{nT}}{\frac{\delta_G}{\delta_B}} = t_D = \frac{t_{nT}}{l}[km] \quad (1)$$

where:

t_D – actual time until piston’s seizure,

l – forces proportion indicator equal to 0,00409.

Using the same calculation method for time, the following values were obtained:

- time until cylinder’s repair t_D = 2420 h,
- distance until cylinder’s repair S_D = 169370 km.

Weibull Analysis

From tribological tests for 10 samples the friction distance and weight decrease during the tests. The results arranged in incrementing order and stages of calculation are shown in Fig. 6.

The cells holds the following data:

A1 – weight decrease during the tribological testing, g,

B1 – friction distance from tribological tests, m,

C1 – rank, values assigned to increasing friction distance,

D1 – mean rank calculated from the formula: =(B2-0,3)/(10+0,4).

With the use of AnalysisToolPack and Regression tools in MS Excel calculation sheet, the univariate analysis of variance, which dialog window has been shown in Fig. 7.

	A	B	C	D	E	F	G
1	weight decrease	road friction	rank	mean rank	1/(1-mean rank)	ln(ln(1/1-mean rank))	ln(road_ friction)
2	0,0425	137090,685	1	0,06731	1,072165	-2,663843	11,8284
3	0,0414	140733,191	2	0,16346	1,195402	-1,723263	11,8546
4	0,0405	143860,596	3	0,25962	1,350649	-1,202023	11,8766
5	0,0401	145658,853	4	0,35577	1,552239	-0,821667	11,8890
6	0,0399	146023,913	5	0,45192	1,824561	-0,508595	11,8915
7	0,0389	149777,741	6	0,54808	2,212766	-0,230365	11,9169
8	0,0384	151727,972	7	0,64423	2,810811	0,032925	11,9298
9	0,0364	160064,674	8	0,74038	3,851852	0,299033	11,9833
10	0,0358	162747,322	9	0,83654	6,117647	0,593977	12,0000
11	0,0344	169370,760	10	0,93269	14,857143	0,992689	12,0398

Fig. 6. Calculation for Weibull coefficient analysis

	A	B	C	D	E	F	G
1	***Regression Statistic***						
2	Multiple R	0,9434907					
3	R square	0,8901747					
4	Adiusted R square	0,8764466					
5	Standard Error	0,3919361					
6	Obserwations	10					
7	***ANOVA***						
8		*df*	*SS*	*MS*	*F*	*Significance F*	
9	Regression	1	9,96079	9,96079	64,843	4,1658E-05	
10	Residual	8	1,22891	0,15361			
11	Total	9	11,1897				
12		*Coeficiencs*	*Standard Error*	*t Stat*	*p-walue*	*Lover 95%*	*Upper 95%*
13	Intercept (b)	-185,92074	23,0239	-8,07512	4,1E-05	-239,014	-132,828
14	ln(road_friction)	15,552181	1,93134	8,05251	4,2E-05	11,0985	20,0059
15	**Beta (Shape Parameter)**	**15,552181**	$\beta = \ln(road\_friction)$				
16	**Alpha (Characteristic Life Parameter)**	**155537,36**	$\alpha = \exp(-\frac{b}{\beta})$				

Fig. 7. Regression analysis, indicators α and β Weibull statistics

Knowing α and β the probability calculator had been constructed, then the distance values were introduced there (from 100000 to 190000 with increment of 10000) and with the use of function =WEIBULL() in MS Excel calculation sheet the probability of survival and inverse function, that defines the probability of destruction. For the defined probabilities (0,01 to 0,99) the working distance was defined, for which assumed probability is corresponding (Fig. 8).

	A	B	C
1	Work road [km]	Propability of survival	Failure propability
2	100000	0,001038308	0,998961692
3	110000	0,004563576	0,995436424
4	120000	0,017545052	0,982454948
5	130000	0,059612990	0,940387010
6	140000	0,176842940	0,823157060
7	150000	0,433940261	0,566059739
8	160000	0,788305392	0,211694608
9	170000	0,981425742	0,018574258
10	180000	0,999938475	0,000061525
11	190000	1	0,000000000
13	Propability "p"	Road action D_d [km]	
14	0,01	**171585,7429**	
15	0,1	**164106,2314**	$D_d = \alpha \cdot (-\ln(p))^{\frac{1}{\beta}}$
16	0,5	**151914,7198**	
17	0,9	**134583,9419**	
18	0,99	**115711,2572**	

Fig. 8. Probability calculator in MS Excel

Using the formula (1) and assuming D_d equal to 115711,25 (for p=0,99 – Fig. 8) and average daily distance covered by the car as 100km the theoretical warrantee time has been determined:

$$Warantee\_time = \frac{115711{,}26[km]}{100\frac{km}{day} \cdot 365\frac{days}{year}} = 3{,}17\_years \qquad (2)$$

5. Summary

The possibility of evaluation of abrasive wear-off is often a challenge to the engineers when it comes to defining the „life time" of the designed element. The main problem however is the fact, that given material does not have constant wear-off, but it depends on the degradation level of the abrasive couple of two interacting with each other materials. In this dissertation the abrasive system was the AlSi17Cu5Mg and ductile cast iron EN-GJN-200. The interaction of these elements reflected the friction between the rings and cylinder's plane. To simplify the research it was assumed, that there are dry friction conditions.

On the research, on the basis of 10 measurements of material wear-off the statistical survival analysis has been conducted, defined with Weibull module. Therefore the results obtained from the operation worthiness distance of the motor were implemented to MS Excel and 10 results with operation worthiness of the cylinder (Fig. 6). Using the regression analysis and Weibull analysis base (Fig. 7) the α and β parameters were determined, on the basis of which, with the use of WEIBULL() function the probability of survival of defined number of kilometers was defined. It was proven, that 99% of tested abrasive systems will survive 115711,26 km. Assuming average, daily distance as equal to 100km, and using the formula (2) the theoretical warrantee period was defined as 3,17 years.

In the end we can state, that due to desired, ever increasing „survival time" of the machines elements, the estimation of the material reliability is one of basic issues in the application of modern material engineering. Since it is a „lifetime" of the product that the profitability of the whole project is depending on, even the superexcellent construction solutions will never serve their purposes well, if the choice of the construction materials will not ensure maximum extension of the construction lifetime.

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