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Research on Wear of Liners in Diesel Engines During Start-ups

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Abstract This paper presents the methodology and results of tests of the start-up wear of the cylinder liner in vehicle diesel engines. The conducted tests were aimed at determining the starting wear of the cylinder liner, as well as the influence of the starting temperature and other factors on the observed wear value.

Keywords diesel engine, cylinder testing, starting wear testing

JEL L62, L90, C15

1. Introduction

The start-up of a vehicle internal combustion engine is a transitional process accompanied by the occurrence of many negative tribological processes. At the beginning of the start-up, due to insufficient amount of engine oil (inertia of the engine lubrication system) and too low relative velocity of the moving surfaces of its tribological pairs, the occurrence of the so-called boundary friction is noted [5,6,10].

As the engine oil flows to the engine tribological nodes, the boundary friction turns into mixed friction. Only when a sufficient relative velocity and amount of lubricating oil are achieved between the moving surfaces of kinematic pairs (usually occurring after the engine start-up), favourable conditions for the occurrence of liquid friction appear [7,10,11]. The described transition from boundary friction (in extreme cases from dry friction) to mixed friction with a low percentage of liquid friction causes that adhesive and abrasive wear can be observed in the tribological nodes of the internal combustion engine during start-up, in addition to corrosive wear in the PRC system [6,8].

As a result, the start-up wear is characterized by a higher wear rate than that occurring during the normal operation of the internal combustion engine The start-up wear of the cylinder liner bearing surface during a single start of an internal combustion engine constitutes from 8% to 75% of its total operational wear. The values of the equivalent start-up wear range from a few to several hundred or even several thousand kilometres of vehicle mileage or several (up to 10) hours of operation on an engine test bench [6,11].

2. Research objects and the methodology of research

The research was conducted on 359M and 4CT90 diesel engines. The basic technical parameters of these engines are presented in Table 1.

Table 1. Selected technical parameters of the 359M and 4CT90 engines

Specification	Engine parameter value	
	359M	4CT90
Number of cylinders [pcs.]	6	4
Cylinder diameter [mm]	110	90
Stroke [mm]	120	95
Displacement [dm^3]	6.842	2.417
Compression ratio	17	20.6
Rated power [kW]	110	66
Rotational speed of rated power [rpm]	2800	4100
Maximum torque [Nm]	440	195
Rotational speed at the max torque [rpm]	1800-2100	2500
Idle speed [rpm]	500-600	800±20
Maximum rotational speed [rpm]	3100	4100
Compression pressure [MPa]	2.4	3.0
Oil pressure in the lubrication system [MPa]	0.2-0.	0.38-0.

The PRC system of the 4CT90 engine uses a piston with two sealing rings and one wiper ring. In the PRC system of the 359M engine, the piston is sealed in the cylinder liner by three O-rings and includes one wiper ring.

The wear assessment of cylinder liner bearing surfaces during the start-up of the tested engines was carried out on a special engine testbed at the Department of Internal Combustion Engines, Lublin University of Technology. Electronic measurement and control systems used on the stand allowed for continuous control of the temperature of the coolant and engine oil. A heater and a water cooler in the engine oil pan, as well as a heater in the engine coolant heat exchanger and a water pump operating when the engine is stopped, were installed to stabilize the above-mentioned temperatures. Fluctuations in coolant and lubricating oil temperatures during the series of start-ups did not exceed ± 2.5°C.

For the tested diesel engines, a series of start-ups was performed with the parameters shown in Table 2. After starting, the engine idled for several dozen seconds. After the engine was stopped, it was brought back to the assumed start-up temperature.

Table 2. Parameters of the various start-up series of the 359M and 4CT90 engines

Series 359 engine	Number of engine start-ups	Water and lubricating oil temperature [K]	Series 4CT90 engine	Number of engine start-ups	Water and lubricating oil temperature [K]
Series no. 1	500	283 (10°C)	Series no. 1	1000	291 (18°C)
Series no. 2	700	293 (20°C)	Series no. 2	1000	308 (35°C)
Series no. 3	1000	333 (60°C)	Series no. 3	1000	328 (55°C)
			Series no. 4	1000	248 (75°C)

3. Methodology of testing the wear of cylinder liners

In the conducted tests, the increase in their internal diameter was assumed as a measure of the wear of cylinder liners in the 359M and 4CT90 engines. In order to determine this increase, the surface of individual cylinder liners was cut with a diamond blade, creating the so-called "artificial bases". A special UPOI6 device was used for this purpose. The applied wear assessment method is characterized by an accuracy of 1 μm.

In order to avoid complete disassembly of the engines, the "artificial bases" were cut only after removing the head. This was done in accordance with the Industry Standard BN-79/1374-04, perpendicular to the direction of friction in measurement planes (levels) at different heights of the cylinder liner measured from the block surface and for four directions - parallel (A-A) to the crankshaft axis, perpendicular (B-B) to this axis and at an angle of 45°C to the crankshaft axis (C-C, D-D), as shown in Figure 1.

The first three measurement planes for the 4CT90 engine and the four measurement levels for the 359M engine correspond to the centers of their piston ring positions at TDC. The greater number of measurement levels of the 4CT90 engine resulted from better technological possibilities of cutting the "artificial base". The "artificial bases" cut in each measurement plane were marked sequentially from 1 to 8 clockwise, starting from the base on the A-A direction closest to the front of the engine.

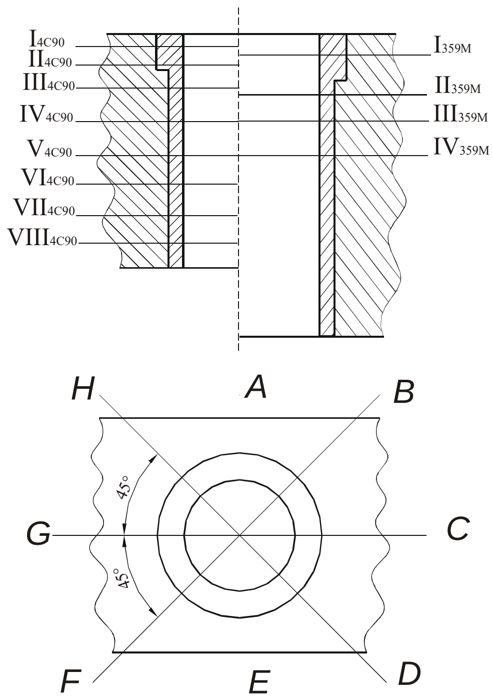

Figure 1. Scheme of cutting artificial bases on the surface of cylinder liners of the tested engines; height (level) of notching the bases along the 4CT90: – 23 mm, III_{4CT90} – 30 mm, IV_{4CT90} – 40 mm, V_{4CT90} – 50 mm, VI_{4CT90} – 60 mm, VII_{4CT90} – 70 mm and the 359M engine: I_{359M} – 23 mm, II_{359M} – 36.5 mm, III_{359} – 55.5 mm.

The first three measurement planes for the 4CT90 engine and the four measurement levels for the 359M engine correspond to the centers of their piston ring positions at TDC. The greater number of measurement levels of the 4CT90 engine resulted from better technological possibilities of cutting the "artificial base". The "artificial bases" cut in each measurement plane were marked sequentially from 1 to 8 clockwise, starting from the base on the A-A direction closest to the front of the engine.

After each series of start-ups, the engine head was removed and the changes in the length of the "artificial base" were read, which made it possible to assess the wear of the cylinder liner surface (increase in its internal diameter). The value of the single radial wear of the liner surface is calculated from the following formula, see Figure 2:

$$z_{ri} = \frac{1}{8} \cdot \left(\frac{1}{r} - \frac{1}{R} \right) \cdot \left(l_p^2 - l_k^2 \right), \qquad (1)$$

where:

z_{ri}– value of the ***i***-th radial wear of the cylinder liner [μm],

r – knife radius 9.4 [mm],

R – radius of curvature of the tested surface 45 or 55 [mm],

l_p – initial cut length [μm],

l_k – end length of the cut, [μm].

The value of wear (increase) of the inner diameter of the cylinder liner is:

$$d_i = z_{rxj} + z_{rxk} \;, \qquad (2)$$

where:

d_i – value of the ***i***-th cylinder liner wear (increase in the inner diameter) [m],μ

z_{rxj}– value of radial wear at the level ***x*** = I, II, ..., VII and direction j = 1,..,4μm],

z_{rxk}– value of radial wear at the level ***x*** and direction ***k = j + 4*** [μm].

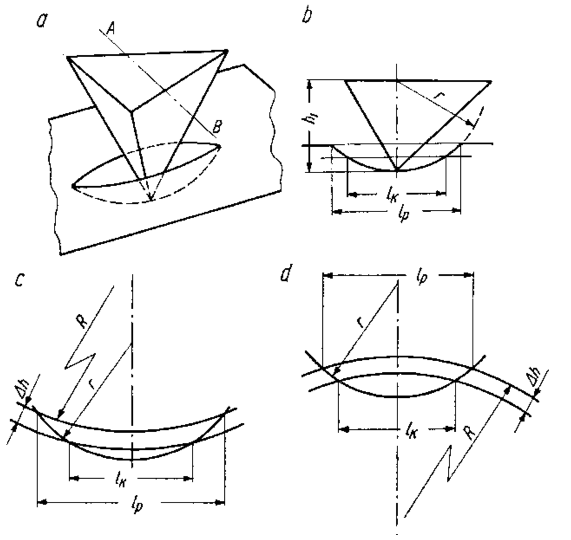

Figure 2. Scheme for calculating the depth of cuts; **R** – radius of curvature of the tested surface, **r** – knife radius, $\mathbf{l_p}$ – initial cut length, $\mathbf{l_k}$ – final cut length, $\mathbf{h_1}$ – knife height, **Δh** – linear wear value

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4. Research results

After reading the changes in the length of the "artificial base", the wear of the cylinder liner was calculated using the formulas (1) – (2). Then, a preliminary statistical analysis of the obtained results was carried out using the STATISTICA software package, and the elimination of the "gross error" results was performed by calculating the lower limit of the confidence interval:

$$d_d = \bar{d} - t_{1-\alpha_{pi0}/2} \cdot \sigma_d \cdot \sqrt{\frac{n}{n-2}} \;, \qquad (3)$$

and the upper end of the confidence interval:

$$d_g = \bar{d} + t_{1-\alpha_{pi0}/2} \cdot \sigma_d \cdot \sqrt{\frac{n}{n-2}} \;, \qquad (4)$$

where:

d_d –lower end of the confidence interval,

d_g – upper end of the confidence interval,

$t_{1-\alpha pi/2}$ – quantile of Student's t-distribution with n-2 degrees of freedom.

The results from calculations of the confidence interval limits were obtained at the confidence level $\alpha_{pi/2}$=0.1 where $t_{1-\alpha pi/2}$ = 1.659 [1]. After taking into account and rejecting the questionable results from further analysis, the final selected parameters of the position and the spread of the start-up wear of the cylinder liners were calculated. Additionally, to compare the obtained values, the results of the cylinder liner wear of the 359M engine in series 1 and 2 were calculated per 1000 starts. The results of the statistical calculations are presented in Tables 3 and 4.

It should be emphasized that at a temperature of 75°C for the series of 4 starts of the 4C90 engine, no case of radial wear was found. The measurement method used in the research, based on "artificial bases", turned out to be too "sensitive".

Table 3. Parameters of the position and dispersion of the start-up wear of the cylinder liner after the rejection of questionable results for the 4CT90 engine [4]

	Series no. 1	Series no. 2	Series no. 3
Average value d [μm]	3.448	1.936	1.037
Variance Var [μm2]	2.138	2.232	1.178
Standard deviation s_d [μm]	1.462	1.494	1.085
Standard error d_d [μm]	0.151	0.143	0.102
Median m_e [μm]	2.357	2.149	0.0
Mode [μm]	2.243	0.0	0.0
Coefficient of variation v [%]	42.40	77.16	104.62
Max.value [μm]	6,675	4.658	2.736
Min. value [μm]	1.808	0.0	0.0

Table 4. Parameters of the position and dispersion of the start-up wear of the cylinder liner after the rejection of questionable results for the 359M engine [3]

Average value [μm]	Series no. 1	Series no. 2	Series no. 3
Variance Var [μm2]	7.645	6.397	6.419
Standard deviation s_d [μm]	0.207	4.318	3.915
Standard error d_d [μm]	0.445	2.078	1.978
Median m_e [μm]	0.051	0.222	0.214
Mode [μm]	7.598	5.656	6.099
Coefficient of variation v [%]	7.919	5.721	6.007
Max.value [μm]	máj.82	32.48	30.81
Min. value [μm]	9.406	11.116	sep.44
	6.728	2.762	2.231

4.1. Analysis of the variance of the obtained research results

In order to determine the influence of temperature and other grouping factors (cylinder, level, direction) on the wear of the engine cylinder liner during its start-up, an analysis of variance was performed using the STATISTICA software package. The first step in this analysis was to investigate whether the data came from a normally distributed population and whether all groups of results had the same variance.

The significance level was assumed to be α = 0.05. The chi-square test χ^2 was used for compliance testing with a normal distribution. For testing the homogeneity of variance, the Bartlett **B** [2] test was adopted (due to the unequal number of results in the analyzed groups).

The results of the analysis for the adopted temperature as the grouping factor for the tested engines are presented in Tables 5 and 6.

Table 5. Normal and uniformity test results for wear on the 4CT90; grouping factor – engine temperature

	Normality (N)		Homogeneity (J)		Decision	
	χ^2	value p	B	value p	N	J
Series I	41.13	0.000	12.73	0.001	no	no
Series II	59.86	0.000			no	
Series III	162.0	0.000			no	

Table 6. Normal and uniformity test results for wear on the 359M engine; grouping factor – temperature

	Normality (N)		Homogeneity (J)		Decision	
	χ^2	value p	B	value p	N	J
Series I	3.520	0.1720	141.0	0.00	yes	no
Series II	3.437	0.0637			yes	
Series III	8.082	0.0886			yes	

Based on the results presented in Tables 5 and 6, it is seen that the observed values of the wear of cylinder liner diameters for the 359M engine can be adjusted with the normal distribution, as opposed to the wear in the 4CT90 engine. This is confirmed by earlier studies [3,4]. In the statistical calculations for the analysed engines, it was also found that the normality tests were not met for the following grouping factors: cylinder, level and measuring direction.

Since the assumptions of the classic analysis of variance for the observed wear of the cylinder liner diameters of the 4CT90 and 359M engines during start-up were not fulfilled, a non-parametric method was used in the further analysis of variance using the Kruskal-Wallis **K-W** [2]. The results of this analysis are presented in Tables 7 and 8.

When analysing the results of the variance analysis presented in Table 7, it can be concluded that the temperature has a significant impact on the wear observed during the start-up of the 4CT90 engine.

Table 7. Kruskal-Wallis test results for 4CT90 engine wear (various grouping factors)

Grouping factor	K-W	p value	The influence of the factor on wear
Temperature	102.06	0.0000	**significant**
Cylinder	20.519	0.0001	**significant**
Cylinder in series I	14.751	0.0021	**significant**
Cylinder in series II	12.036	0.0073	**significant**
Cylinder in series II	5.249	0.1545	insignificant
Level	6.120	0.4098	insignificant
Level in series I	14.1418	0.0281	**significant**
Level in series II	3.017	0.8066	insignificant
Level in series III	7,912	0.2446	insignificant
Direction	1.800	0.6148	Insignificant
Direction in series I	2.6954	0.4410	Insignificant
Direction in series II	2.5255	0.4707	Insignificant
Direction in series III	0.7878	0.8524	Insignificant

During the start-up, the influence of another grouping factor, i.e. the cylinder, on the wear values of the cylinder liner is additionally observed. This is probably due to the lower lubrication of the last cylinder liner. Figures 3, 4 and 5 show categorized frame charts the value of cylinder liner wear for two grouping factors (temperature and cylinder for start-ups at 18°C and 35°C) of the 4CT90 engine.

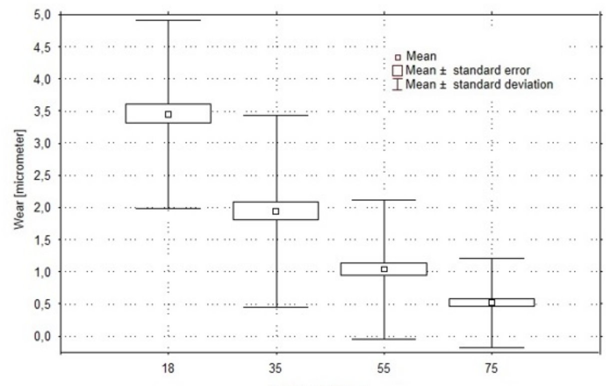

Figure 3. Categorized box plot for the temperature grouping factor and the dependent variable – wear on the cylinder liner diameter of the 4CT90 engine during its start-ups

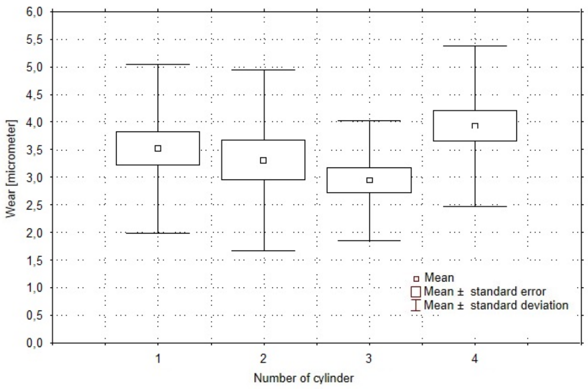

Figure 4. Categorized box plot for the cylinder grouping factor and dependent variable – wear on the cylinder liner diameter of the 4CT90 engine during its start-ups in series I

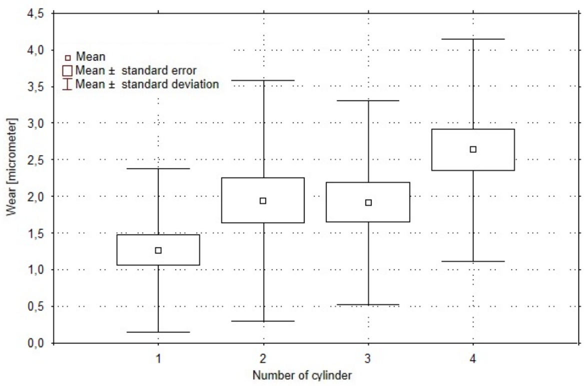

Figure 5. Categorized box plot for the cylinder grouping factor and dependent variable – cylinder liner wear on the cylinder liner diameter of the 4CT90 engine during its start-ups in series II

Table 8. Kruskal-Wallis test results for 359M engine wear (various grouping factors)

Grouping factor	K-W	p value	The influence of the factor on wear
Temperature	22.297	0.000	**significant**
Cylinder	6.467	0.2633	insignificant
Cylinder in series I	2.683	0.7487	insignificant
Cylinder in series II	14.040	0.0154	**significant**
Cylinder in series III	5.889	0.3376	insignificant
Level	2.753	0.4308	insignificant
Level in series I	0.775	0.8553	insignificant
Level in series II	1.110	0.7746	insignificant
Level in series III	1.017	0.7970	insignificant
Direction	1.984	0.5756	insignificant
Direction in series I	2.059	0.5602	insignificant
Direction in series II	2.045	0.5630	insignificant
Direction in series III	5.045	0.1685	insignificant

When analysing the results of the variance analysis presented in Table 8, it can be concluded that the temperature has a significant impact on the wear observed during the start-up of the 359M engine. Figure 6 shows the categorized box plot of the cylinder liner wear value for the grouping factor, i.e. the 359M engine start-up temperature.

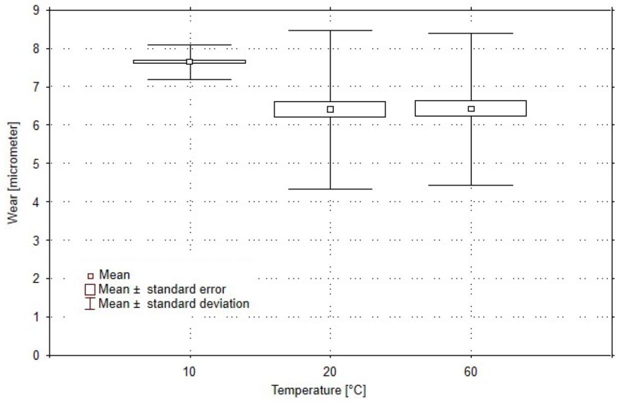

Figure 6. Categorized box plot for the temperature grouping factor and the dependent variable – wear on the cylinder liner diameter of the 359M engine during its start-ups

5. Conclusions

Based on the performed tests and the conducted statistical analysis of the obtained results from the cylinder liner wear assessment in 4CT90 and 359M diesel engines, it can be concluded that:

- The start-up wear of the cylinder liner bearing surface, measured by the increase in its internal diameter, depends significantly on the value of the engine start-up temperature. This is due to the increase in the influence of negative tribological processes on the wear intensity of the finishing coats as the temperature drops.
- The start-up wear value also depends on the type of injection. The use of indirect injection in a split combustion chamber (4CT90 engine) limits the variability of dynamic loads occurring in the PRC system. This improves the lubrication conditions in its tribological pairs and reduces the start-up wear.
- The value of the starting wear of cylinder liners of the tested engines does not depend on the direction and level of assessment. This observation is quite interesting because, according to other researchers, the wear value along the running surface of the cylinder liner during operation depends on the position in relation to the surface of the engine block (the TDC of the top ring).
- The occurrence of a significant field of scattering of the observed values of cylinder liner wear during engine start-up results from the complex friction process in the PRC system, and the accuracy of the "artificial base" method.

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