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A METHOD OF AUTOMOTIVE ENGINE LIFE FORECASTING ON THE BASIS OF LABORATORY START-UPS TEST

Grzegorz Koszałka, Andrzej Niewczas

Lublin University of Technology, Department of Combustion Engines and Transport
Nadbystrzycka Street 36, 20-618 Lublin, Poland
tel.+48 81 5384259, fax: +48 81 5384258
e-mail: g.koszalka@pollub.pl, a.niewczas@pollub.pl

Paweł Kordos

Lublin University of Technology, Department of Fundamentals of Technology
Nadbystrzycka Street 38, 20-618 Lublin, Poland
tel.+48 81 5384490, fax: +48 81 5384671
e-mail: p.kordos@pollub.pl

Abstract

The results of previously conducted research shows that in the case of automotive engines wear accompanying engine start-ups has significant contribution to the total wear of cylinder liner. Thus, it was assumed that wear of the liner measured after high number of start-ups can be representative for given conditions of engine operation in the vehicle and can be used to forecast engine life. The paper describes a new method of automotive engine durability prediction on the basis of wear measured after so called start-ups test. The start-ups test consists of series of repeatable cycles during which engine is started-up in precisely established temperature and operates for short time with no load and then is shut down and cooled down. To conduct the new test it is indispensable to obtain data regarding start-up conditions. But these data can be precisely determined on the basis of simple measurements made on any existing engine installed in a vehicle used in expected way. Moreover, the cost of the new test is significantly lower (minimal fuel consumption, engine does not have to be installed on dynamometer stand) and duration is shorter than in the case of standard tests. Considering advantages of the new start-ups test, it can be recommended as a part of the test stand reliability research of automotive engines. The developed method is simple and short and can be a complementary one to existing standard reliability research methods.

Keywords: *combustion engines, cylinder liner, life estimation, start-ups, wear*

1. Introduction

Development of laboratory research methods, which would allow forecasting of durability of an automotive engine in more precise manner than it was done so far, is an important issue in the field of engine design and manufacturing technology. Investigations of wear progress and durability estimation are usually done within more complex reliability research. Research of engine reliability can be divided into two groups. First group is constituted by the investigations in which engine is installed in a vehicle, and includes: investigations in normal service conditions and in conventional conditions. The second group consists of research in which engine is not installed in a vehicle but on a test stand. Test-stand engine reliability research can be performed in conditions reconstructing conditions of real operation and in conventional conditions (Fig. 1).

Test-stand reliability researches of engines in conventional conditions, so called reliability tests, are commonly used. Reliability tests usually consist of repeated many times cycles in which engine works in established conditions. Most of engine manufacturers have their own test procedures. Sometimes such procedures are formulated as standards. Fig. 2 shows examples of test cycles according to Cummins and Polish standard.

The aim of these reliability tests is not determination of statistic reliability indexes, probabilities of failures of different engine components because credible results concerning this matter are available only from normal service. The main goal of the reliability tests is to discover faults in design and material specification, especially to check, whether there are no fatigue defects and if the wear of the components does not limit expected engine life. That is the reason to run the engine at high loads. Evaluation of the engine after the test is, among other things, done on the basis of wear measurements of chosen components, e.g. cylinder liner [1].

Wear values obtained during reliability tests are therefore, in more or less open way, used for the assessment of engine durability. However, estimation of the durability on this basis is difficult and usually inaccurate, as engine operating conditions during the test differ significantly from those in normal using in a vehicle. Moreover, there are very few engine start-ups during these tests. In case of automotive engines, wear of the cylinder liner surface related to start-ups constitutes from 30% to 70% of the total wear [5].

Considering large share of start-up wear in the total wear of the automotive engine, the authors have decided to elaborate a complementary method of test-stand reliability research, which would allow evaluating of the engine durability on the basis of wear accompanying start-up process.

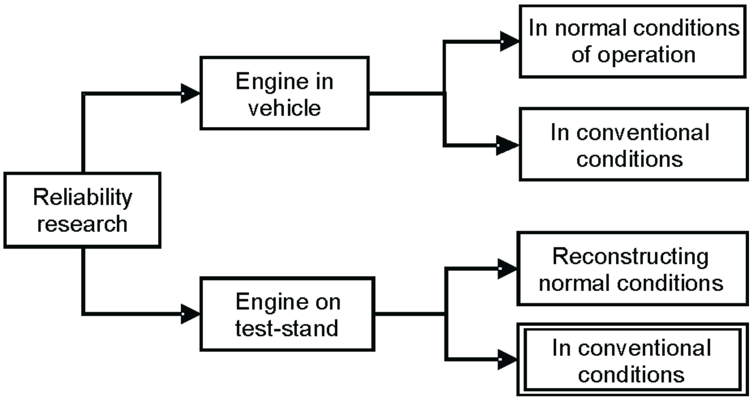

Fig. 1. Division of reliability research of automotive engines in respect to methodology

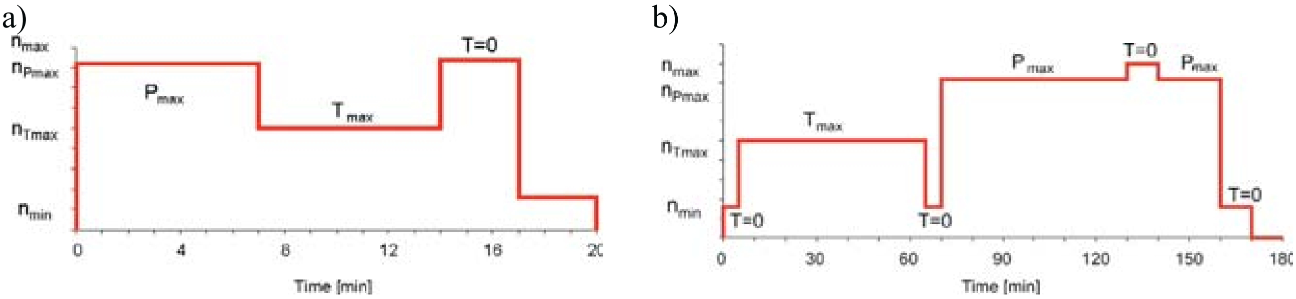

Fig. 2. Engine operating conditions during reliability tests: a) Cummins, b) Polish standard

2. Service research

The goal of service research was to identify normal engine operating conditions and to determine normal service wear of cylinder liners. Cylinder liner is commonly treated as representative engine component because consequences of its wear are the most common reason of withdrawing the whole engine from use [6].

Research was done using delivery vehicles of maximum total weight of 2.9 t, equipped with 4-cylinder diesel engine with swept volume of 2.4 dm^3 and rated power of 66 kW at 4100 rpm. Investigated vehicles belonged to the postal company and worked in similar conditions. Vehicles were used 5 days a week with average daily mileages of 240 km and annual mileages of 55000 km. Research was done for several years and practically did not disturbed normal vehicle service.

So as to determine number and conditions of start-ups and operating conditions of the engine, vehicles were equipped with recording device registering: time corresponding to switching on and off the starter, rotational speeds of the crankshaft and drive shaft, oil pressure and temperature, coolant temperature and position of the control lever of the injection pump. Gathered data made it possible to form a time density characteristics of the engine operating conditions (Fig. 3) [2].

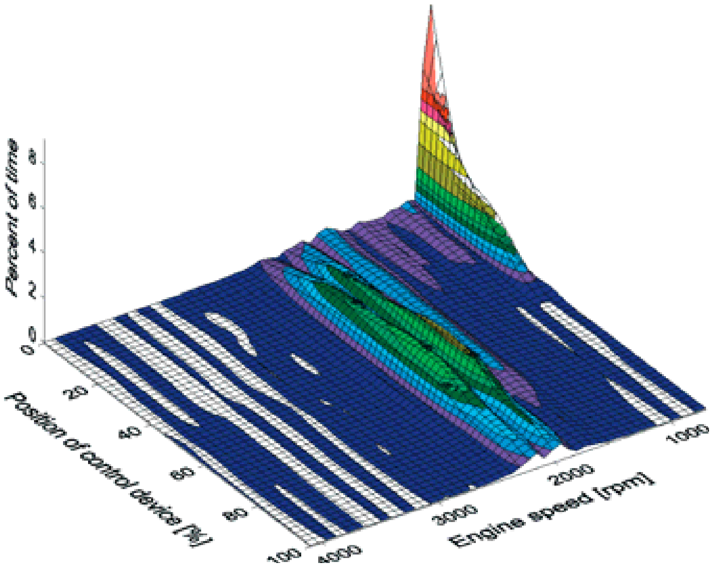

Fig. 3. Engine operating conditions in normal service

Temperatures of start-ups and distances covered by vehicles between consecutive start-ups were determined (Fig. 4). It was established that on the average, engine start-up occurred every 7 km. It was also found that 85% of start-ups were done at warm engine (coolant temperature above 70 C) and only 3% of engine starts were done at cold engine - most of them were the first start-ups of the day [3].

After long term operation (250000 km) wear of the cylinder liner was measured in two vehicles. On this basis average wear intensities were calculated, which for the particular vehicles amounted to 2.07 and 2.16 μm/(10000 km). Wear measurements were done after removal of cylinder heads using 2-point bore gauge. Location of measurement points is shown in Fig. 5.

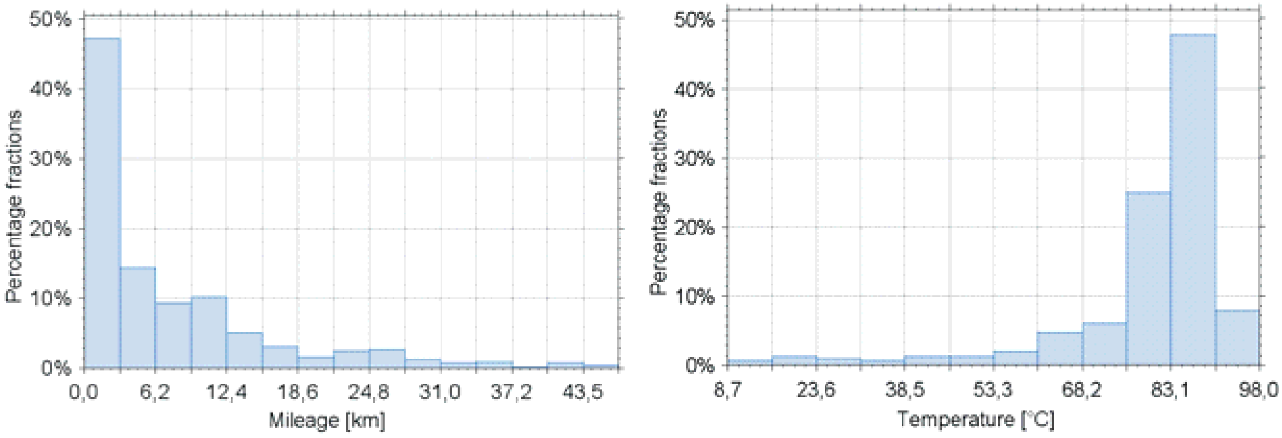
a) b)

Fig. 4. Vehicle mileage between consecutive start-ups of the engine (a) and coolant temperature during engine start-up (b)

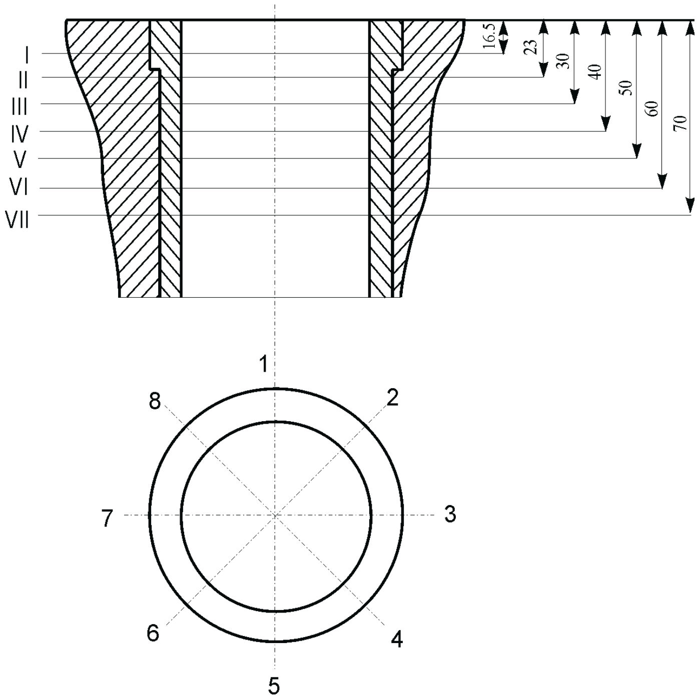

Fig. 5. Location of measurement points on the cylinder surface

3. Test stand research

3.1. Influence of temperature on start-up wear

In order to determine wear of the cylinder liner accompanying engine start-up, a test stand was prepared, which enabled precise control of the engine temperature (oil and coolant) during experiment. Four series of the engine starts were made in strictly defined temperatures: 15, 35, 55 and 75 C. Each series consisted of 1000 start-ups. The engine idled for 15 seconds after starting and then was turned off and cooled or heated to the required temperature. Then next start-up followed. After each series at given temperature the measurement of the cylinder wear was made. The engine used in the experiments was the same type as used in the service research.

Results of the measurements are shown in Fig. 6. The wear accompanying one start-up at 15 C was 7 times higher than at 75 C [4]. The results confirmed common opinion that wear related to the engine start-up strongly depends on the engine temperature.

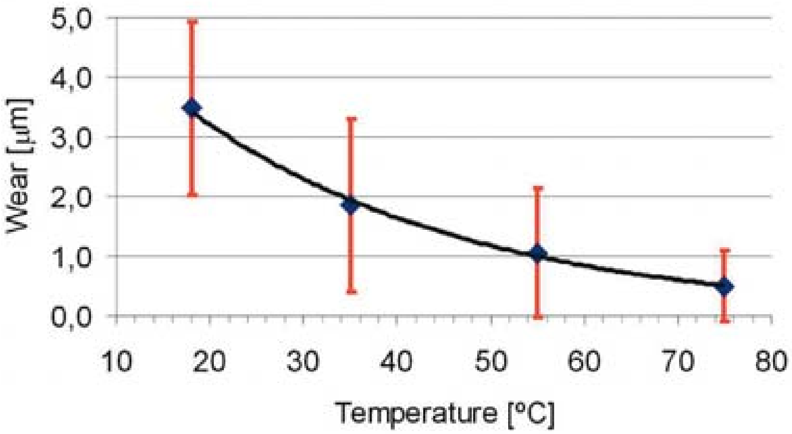

Fig. 6. Start-up wear as a function of engine temperature

3.2. Contribution of start-up wear to the total wear

Fig. 7 presents assumed model of cylinder wear of an automotive engine [7]. In this model the total service wear (W_T) is a sum of wear accompanying engine operation after start-up, so called motion wear (W_R), and increments of wear occurring only during start-ups of the engine - so called start-up wear (W_S):

$$W_T = W_R + W_S \cdot \tag{1}$$

Having number and temperature of start-ups and total cylinder liner wear intensity in long vehicle service (results of service research) as well as the increment of wear accompanying one start-up of the engine at given temperature (result of test stand research) it was possible to evaluate the contribution of start-ups to the total liner wear. In the case of investigated engines this contribution equaled 43%.

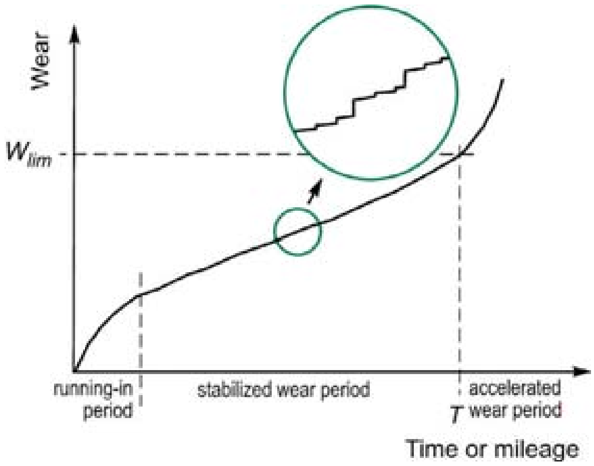

Fig. 7. Model of service wear of the cylinder liner

4. Durability prediction on the basis of reliability test

Wear intensity in standard reliability tests is calculated from the equation:

$$w_t = \frac{W_{test}}{t_{test}}, \tag{2}$$

whereas engine durability, understood as engine working time (vehicle mileage) after which assumed boundary wear is reached, can be evaluated as follows:

$$T_{km} = \lambda \cdot \frac{W_{\lim}}{W_{test}} \cdot t_{test}, \tag{3}$$

where:

w_t - wear intensity in the test, μm/h,
T_{km} - predicted engine durability, km,
t_{test} - duration of the test, h,
W_{test} - wear in the test, μm,
W_{lim} - boundary wear, μm,
λ - coefficient determining correlation between intensities of wear in service and in laboratory test, km/h.

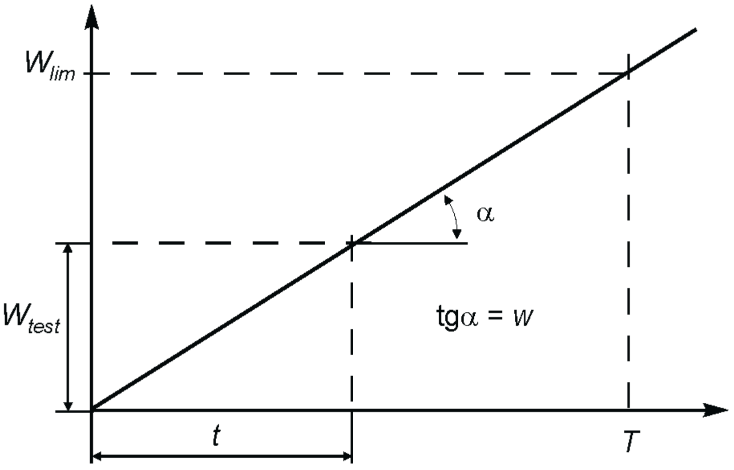

Fig. 8. Principle of durability prediction

Deriving (3), it was assumed that course of wear is steady (constant wear intensity) both during laboratory test and real operation. Results of experiments confirm this assumption within the stabilized wear period of operation (Fig. 7). Therefore, engine before starting the test should be run-in.

So as to use the equation above, one should known boundary wear W_{lim}, which can be assumed with sufficient accuracy for the given engine type. However, the essential problem encountered during evaluation of the wear intensity and engine durability is converting the wear intensity obtained during the test to the wear intensity during normal service, i.e. determining the λ coefficient. Its value, even for the vehicles of the same class, can be included in the wide range.

Moreover, the problem is complicated by the fact that wear forms (e.g. profile of wear along the liner) obtained in standard reliability tests differ significantly from those obtained in real operation (Fig. 11). This creates some problems with determining wear measure of the cylinder. Such measure can be defined as e.g. average wear of the cylinder liner (average value of the wear measurements in all directions and at all heights - see Fig. 5), or as wear value at the height where the wear is largest (such measure is most often accepted in determination of the boundary wear on the basis of measurements made on worn out engines withdrawn from service).

Different wear profiles results from the fact, that engine operating conditions in reliability tests and during operation in the vehicle differ very much (Fig. 9).

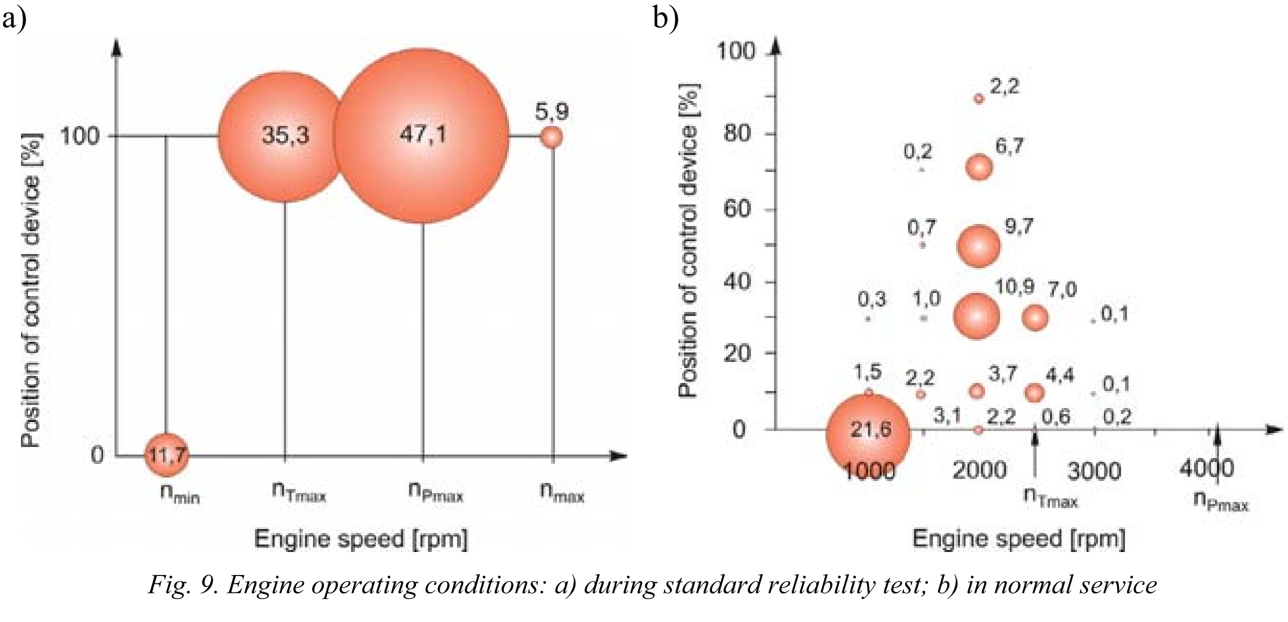

Fig. 9. Engine operating conditions: a) during standard reliability test; b) in normal service

5. Start-ups test

It was assumed that to be able to predict engine service life more precisely, the test should in larger extent consider expected conditions of real operation. Taking into account significant contribution of start-up wear to the total wear and easiness of determination the relations between service conditions and start-up conditions, the start-up wear was taken as a basis of the new test.

It was also assumed, that the new test (so called start-ups test), similarly to the standard reliability tests, would be composed of repeated cycles. Each cycle consists of series of 100 start-ups in four temperatures: 15, 35, 55 and 75 C. Research cycle ends with 15 minutes period of constant engine operation with no load at increased rotational speed (approx. 150 - 200% of idle speed). Numbers of start-ups in each of four temperatures are established on the basis of service research – they equal percentages of start-ups in the following temperatures: below 25 C, 25 - 45 C, 45 - 65 C and above 65 C. After completing the whole test, in the described example consisting of 10 cycles (together 1000 start-ups), measurement of wear is made.

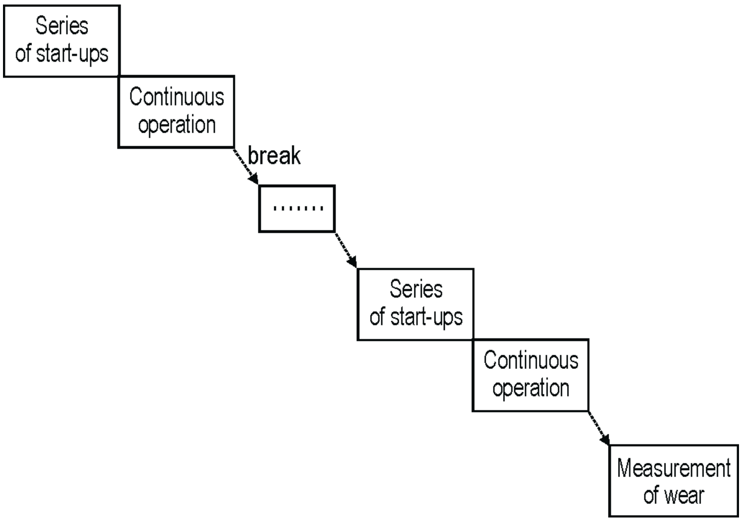

Fig. 10. Scheme of start-ups test

Wear intensity on the basis of the new test is calculated as follows:

$$w_{km} = \frac{10 \cdot W_{testS}}{\alpha \cdot d}, \tag{4}$$

and predicted durability from the equation:

$$T_{km} = 1000 \cdot \alpha \cdot d \cdot \frac{W_{\lim}}{W_{testS}}, \tag{5}$$

where:

w_{km} - estimated wear intensity, μm /(10,000 km),
α - percentage of start-up wear in the total wear,
d - average mileage between successive start-ups, km,
W_{testS} - wear measured in the start-up test, μm,
other denotations as in (3).

So as to carry out the described test and calculate predicted wear intensity and durability, the number and temperature of start-ups, boundary wear and α coefficient should be known.

It should be noticed that start-up percentages at different temperatures and average mileage between start-ups do not depend on the engine but on the way the vehicle is used. For instance, in case of the company owning the investigated vehicles, for every vehicle regardless of the brand and engine type, shares of start-ups at given temperature ranges and average mileage between start-ups were very similar. Boundary wear is determined in the same way as in the case of standard reliability tests. Most difficult is proper estimation of the α coefficient, but it can be assumed that its accuracy is similar to that of λ coefficient.

Engine research was done according to the proposed start-up test. As contribution of start-up wear to the total wear (α) was known for the investigated engine, it is obvious that predicted wear intensity almost equals the intensity of service wear. In the research of prototype engines percentage of start-up wear in the total wear is unknown and α has to be assumed.

Fig. 11 presents wear profiles of the cylinder liner obtained in standard reliability tests, start-ups test and in normal service. It should be noticed that after standard durability tests, where engine worked under severe conditions, the wear measured on the cylinder height corresponding to the dead centers of rings (especially top dead centers) were considerably higher than on the height corresponding to the middle of the piston stroke. In the new start-ups test and during real engine operation in vehicle more uniform profiles of liner wear were obtained.

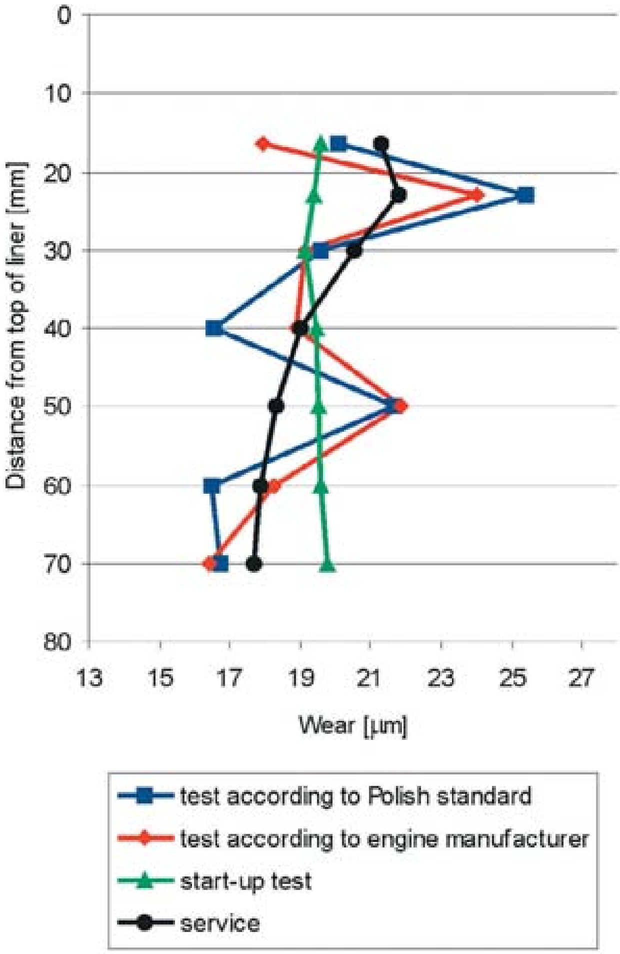

Fig. 11. Wear profiles of cylinder liner after test-stand reliability tests and after long term operation in the vehicle

6. Conclusions

The new start-ups test which was presented in this paper allows taking into account engine start-ups in the reliability research. It is important because start-ups are frequent states during use of the automotive engine and they have a notable contribution to the total wear of the engine. In the case of investigated engines this contribution amounted to 43%.

The advantage of the test is that it makes possible evaluating of the effect of service conditions (number and conditions of start-ups) on the cylinder wear intensity and engine life.

To conduct the new test it is indispensable to obtain data regarding start-up conditions. But these data can be precisely determined on the basis of simple measurements made on any existing engine installed in a vehicle used in expected way.

Moreover, the cost of the new test is significantly lower (minimal fuel consumption, engine does not have to be installed on dynamometer stand) and duration is shorter than in the case of standard tests.

Considering advantages of the new start-ups test, it can be recommended as a part of the test stand reliability research of automotive engines, as a complement one to the standard reliability tests.

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