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ANALYSIS OF SHAFT WEAR IN TURBOCHARGES OF AUTOMOTIVE VEHICLES

Summary. The article presents the results of the investigations of turbocharger shaft bearing using different kinds of lubrication conditions (dry friction and lubrication with different kind of oils). In particular, the wear of the turbocharger shaft surface was evaluated. One of the most frequent failures is the seizure of the turbocharger shaft in the slide bearing, causing its rotation, which leads to destruction of the assembly and costly repairs. On the basis of the conducted tests, it was found that the average value of representative breaks surface on the turbocharger shaft are reduced using of a less viscous oil. Similar situation was seen using new oil instead overworked oil – it had an influence on the value of diameter of breaks.

1. INTRODUCTION

Using turbocharger for engine increases its performance (power and torque), typically about 30% in commercial solution in comparison with engine without a turbocharger. Turbocharger is a type of charging device (Fig. 1). It consists of an exhaust gas turbine that is connected to the compressor. The connection is realized by a common shaft, and both rotors (turbine rotor and compressor rotor) are mounted on a common shaft. Rotors work in their housings. These housings are connected by a central part providing bearing and lubrication [1÷3]. Inside the central housing is a slide bearing and thrust bearing designed to support the turbocharger shaft. The bearing is lubricated with engine oil supplied to the bearings via oil channels that are made inside the housing. This ensures the formation of an oil film (Fig. 2).

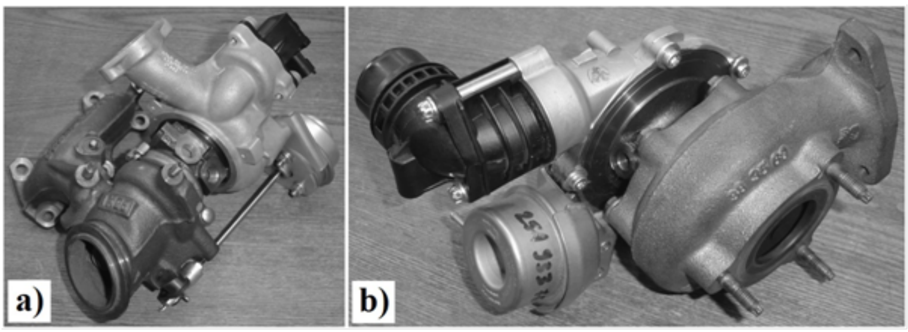

Fig. 1. Turbochargers for passenger cars engine: (a) turbocharger for a two-cylinder engine with integrated exhaust manifold and (b) turbocharger for a four-cylinder engine

The compressor is driven by a turbine that uses the kinetic energy of exhaust gases. About 30% of the energy obtained during fuel combustion is carried by exhaust gases. The turbine therefore uses exhaust gases, and it is the recovery of lost energy. The exhaust gas can propel the turbocharger shaft to revolutions in the very high range [4, 5]. Such rotational speed of the rotor ensures correct work of the compressor and air compression.

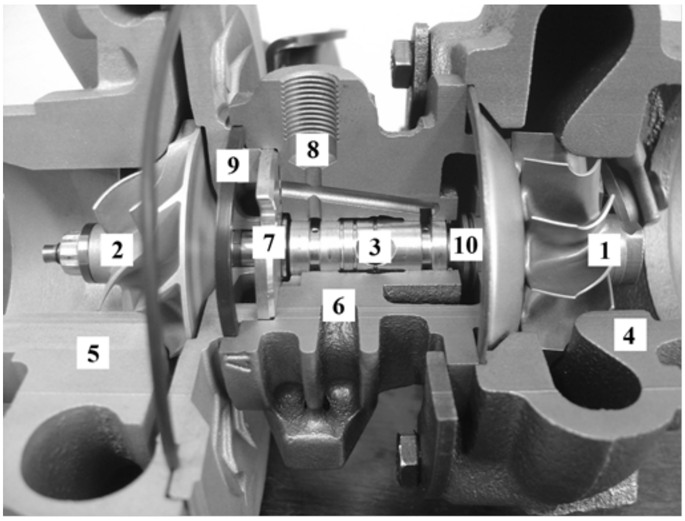

Fig. 2. Construction of turbocharger: 1 – turbine rotor, 2 – compressor rotor, 3 – slide bearing, 4 – turbine housing, 5 – compressor housing, 6 – central housing, 7 – thrust bearing, 8 – oil channel, 9 – sealing ring, 10 – shaft

Turbochargers operate under severe conditions. Nowadays, turbocharger shaft and rotors' speed significantly exceed 200 000 revolutions per minute (up to 300 000 revolutions per minute). In addition, high temperature of exhaust gas acts on the turbocharger elements. In the case of diesel engines, the temperature of the exhaust gas is about 700° C, and in the case of petrol engines, it is about 1000° C. It warms turbocharger elements to a high temperature.

Special materials are used for the construction of turbine housing. They must be primarily heat resistant and have adequate resistance to wear, corrosion and abrasion. For this reason, a material called "Ni-Resist" is used. It contains 11-16% Ni, 2.5% Si, up to 4% Cr, up to 8% Cu, and up to 2% Mn. Other materials are used for compressor housing. In this case, aluminum alloys are most often used. However, turbine rotors are made of materials such as follows:

- "MarM247" (19% Cr, 9% Fe, 5% Nb, 3% Mo, 0.9% Ti, 0.6% Al and 0.05% C),
- "Inconel" (alloy of nickel, cobalt, chromium and iron, nickel content 46÷65%), and
- titanium.

Materials to produce these rotors should have similar properties as housing materials. The best materials for making turbocharger shafts are structural steels for thermal improvement. In contrast, plain bearings are made of bronze. This material must be resistant to high temperatures and pressure and also has resistance to abrasion.

2. MAINTENANCE OF TURBOCHARGERS

Turbochargers are elements that significantly improve the engine's performance; however, it is also important to remember about proper operation of these devices [6÷8]. Only proper operation and quick response to emerging problems will allow to enjoy the benefits of using the turbocharger and extend its life. When using a turbocharger, there are a few rules and actions to remember:

- cooling the turbocharger before stopping the engine,
- warming up the engine before using of turbocharger,
- the required amount of oil in the engine, and
- regular replacement of engine oil.

The most important of them is the rule connected with turbocharger cooling. This rule is often called the "30-second rule". This means that after stopping the vehicle, do not stop the engine immediately. The engine should still run for at least 30 seconds in idle conditions. This will reduce the rotational speed of the turbocharger shaft and rotors to around 30 000 revolutions per minute. During this time, the turbocharger is cooled by gases flowing through the compressor. It is also worth noting that this controlled reduction of the rotational speed of the turbocharger shaft and rotors is of great importance owing to the correct lubrication of the slide bearings with engine oil. For the engine oil to reach the turbocharger, the oil pump must be driven by the engine crankshaft. Engine stoppage terminates the pumping oil and the pressure of lubrication process. In this case, there are no appropriate conditions for the creation of an oil film and lubrication of plain bearings. The higher the rotation speed of the shaft and rotors of turbocharger in the moment of engine stoppage, the longer is time in which these parts rotate without the required lubrication conditions.

Another important rule is about starting the engine after a longer stop or at low ambient temperatures (so-called "cold start"). This is owing to the fact that cold engine oil has high viscosity. For this reason, there are some difficulties with its bringing to the sites that require lubrication (for example, to a turbocharger). It is only when the optimum operating temperature is reached by engine oil that proper lubrication conditions for the engine and turbocharger will be ensured. On the contrary, it is important that because of environmental protection and the process of heating the internal combustion engine, start driving immediately after starting the engine. However, it should be noted that cold engine should not be used with high crankshaft rotational speed.

A very important issue is the kind of engine oil that lubricates and cools the turbocharger. It is worth mentioning at least two aspects, i.e., required amount of oil in the engine and the regular replacement of this lubricant. Too small amount of oil in the engine will result in periodic breaks in lubrication of the engine components and the turbocharger. This is particularly during acceleration, braking, cornering at high velocity and driving up and driving down the hills. It is worth remembering that the lubricating oil accumulates all kinds of dirt and metal filings from the cooperating parts. For this reason, it is very important to regularly change the engine oil and oil filter. Of course, it is also important to use oil with an appropriate class of quality and an appropriate class of viscosity. These activities foster trouble-free operation of the turbocharger.

3. TYPICAL DAMAGE TO TURBOCHARGERS

Abrasive wear is the dominant wear mechanism in tribosystem of shaft and bearings of turbochargers [9]. An example of abrasive wear of shaft and bearing of turbocharger is shown in Fig. 3.

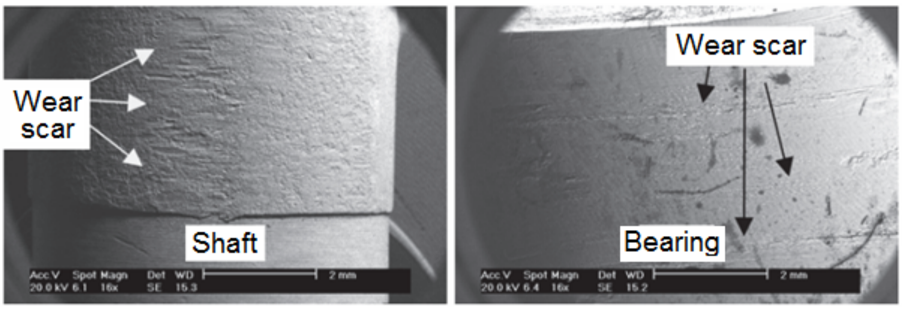

Fig. 3. Worn shaft and bearing of turbocharger [9]

It must be mentioned that there are many different types of turbocharger damages [10÷17]. Each of these damages have a specific cause. The most common damages include the following:

- damage caused by a extraneous body (Fig. 4) or too high temperature (Fig. 5),
- contaminated and overworked engine oil (Fig. 6, 7 and 8), and
- stopping the oil supply (Fig. 6, 7 and 8).

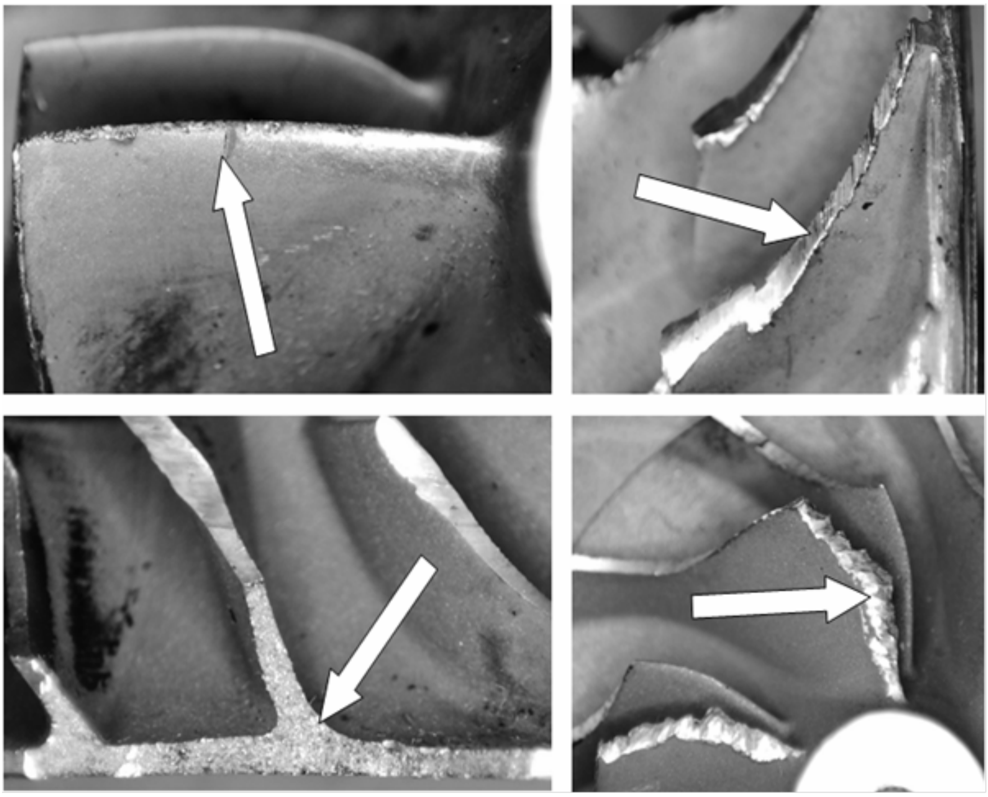

Fig. 4. Compressors rotors damaged by extraneous body (arrows indicate damages of rotor blades)

Damages to the turbine rotor or compressor rotor are very often caused by an extraneous body. The reason may be the following:

- improper replacement of the air filter (contamination in the engine intake system),
- incorrectly assembled turbocharger (with leaving extraneous bodies in the turbocharger), and
- leaking engine intake system (unfiltered air enters to the turbocharger).

Fig. 5. Turbines rotors damaged by too high temperature (arrows indicate damages of rotor blades)

The purity of engine oil is very important. Contamination of engine oil causes damage to the key components of the turbocharger. Contamination of engine oil most often occurs owing to abrasion of the metal parts of the engine or as a result of failure to keep the oil change regime. It is often possible to encounter damage to a new or regenerated turbocharger owing to insufficient cleaning of the oil channels. Therefore, in the case of replacing the turbocharger with a new one or a regenerated one, it is necessary to check the patency of the oil channels and replace the engine oil with a new one.

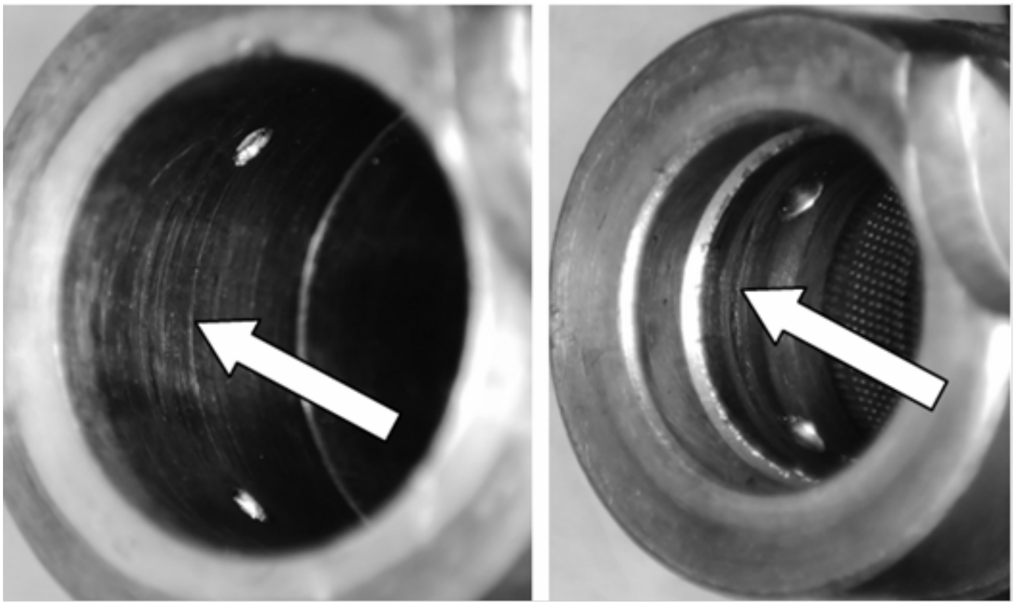

Fig. 6. Damaged slide bearing of turbocharger

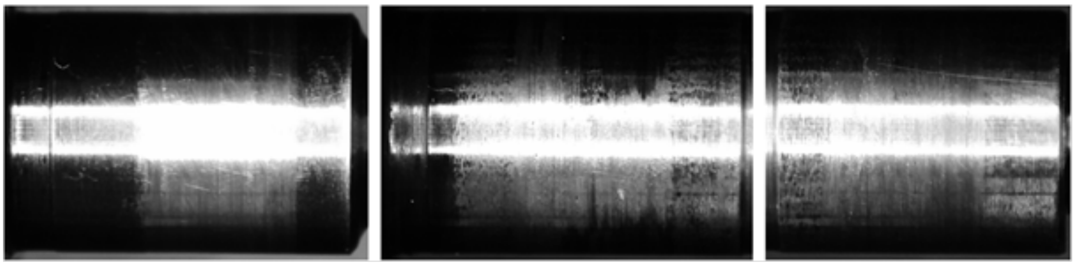

Fig. 7. Damaged shafts of turbochargers (place of cooperation with a slide bearing)

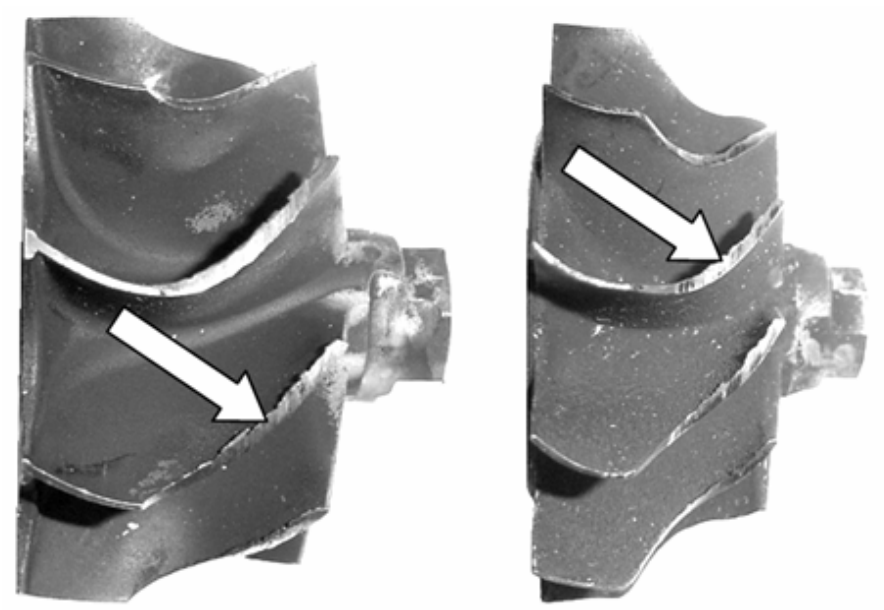

Fig. 8. Turbines rotors damaged by contact with the housing as a result of too big clearance in the bearing

Even a few seconds of lack of lubricating oil supply can result in the appearance of significant turbocharger damage. Breaks in lubrication are mainly caused by the sludge accumulating in the oil supply lines from the engine to the turbocharger.

A frequent case is also the corrosion of the oil line. The effect of this is its crack. In this case, the oil goes to the bearings of the turbocharger at too low a pressure. The required lubrication conditions do not occur. In addition to lubrication, the oil also acts as a cooling agent for the turbocharger. Lack of proper cooling causes overheating of the turbocharger's components, which leads to their damage.

4. INVESTIGATION AND RESULTS

In this work, the analysis of the turbocharger shaft wear was presented. Investigations were done on a special test stand. The idea of test stand is shown in Fig. 9a. In Fig. 9b, the tested friction surface of the turbocharger shaft is indicated.

Wear of shafts was a result of different cases of cooperation with slide bearings. The first case was dry friction (the first part of investigations). The second case was cooperation with lubrication with engine oils (the second part of investigations). During this part, three different kinds of engine oils were used for tests (one new engine oil and two overworked engine oils – mileage 25000 km in urban conditions).

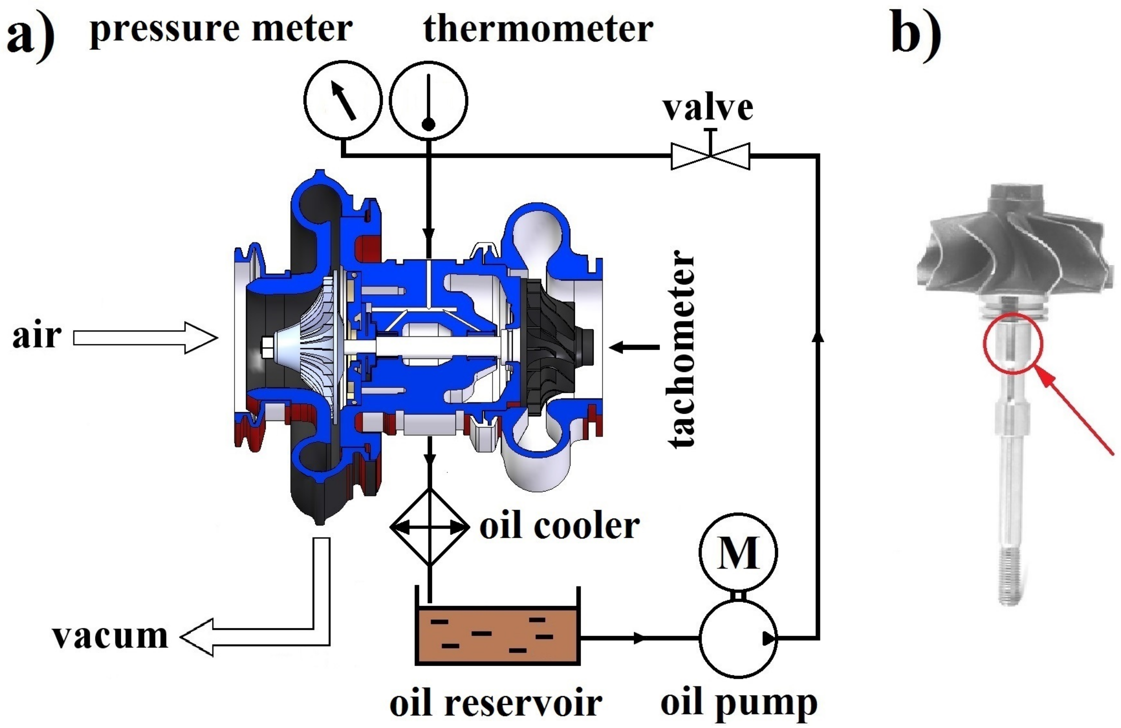

Fig. 9. Scheme of the experimental test stand (a) and the tested friction surface of the turbocharger shaft (b)

For the purpose of this work, a simplified turbocharger model was constructed. It allowed to reconstruct the working conditions (similar to cold start conditions) and lubrication conditions of the turbocharger. Real objects (turbocharger shafts) were used for the tests. A vacuum was used to drive the turbocharger. It affected the turbine of the tested component from the exhaust gas outlet side.

During the tests, the rotational speed of the turbocharger shaft was controlled. In this case, this parameter was measured with using a laser tachometer. The rotational speed of the turbocharger shaft could be adjusted by the vacuum value acting on the turbine.

Moreover, during the second part of investigations, oil temperature and oil pressure were controlled. The initial oil temperature was 25° C, and this parameter has the same value during all tests (possibility set of cooling condition of oil). Oil pressure was 0.4 MPa (possibility set of oil pressure by pump flow and valve). One test lasted 1 hour. Test conditions are shown in Tab. 1.

Table 1

Test conditions

Parameter	Measuring time, s	Rotational speed, min^{-1}	Oil pressure, MPa	Oil temperature, ° C	Lubrication conditions
Value	3600	~ 40000	0.4	25	a) dry friction without oil b) 15W-40 (new oil) c) 5W-30 (overworked oil) d) 0W-30 (overworked oil)

After each test, the turbocharger was disassembled to remove the turbocharger shaft for next examinations. Metallographic examinations were performed on an OLYMPUS CX-40 optical microscope. Next the test results were analysed in the program for quantitative metallographic evaluation (Met-Ilo). Two kinds of examinations were done: values of the surface area of breaks and surface damages were determined and average values of the diameters of the breaks were determined.

The results of examinations of values of the surface area of breaks and surface damages are presented in Fig. 10 and Fig. 11. Calculated values are presented in Tab. 2.

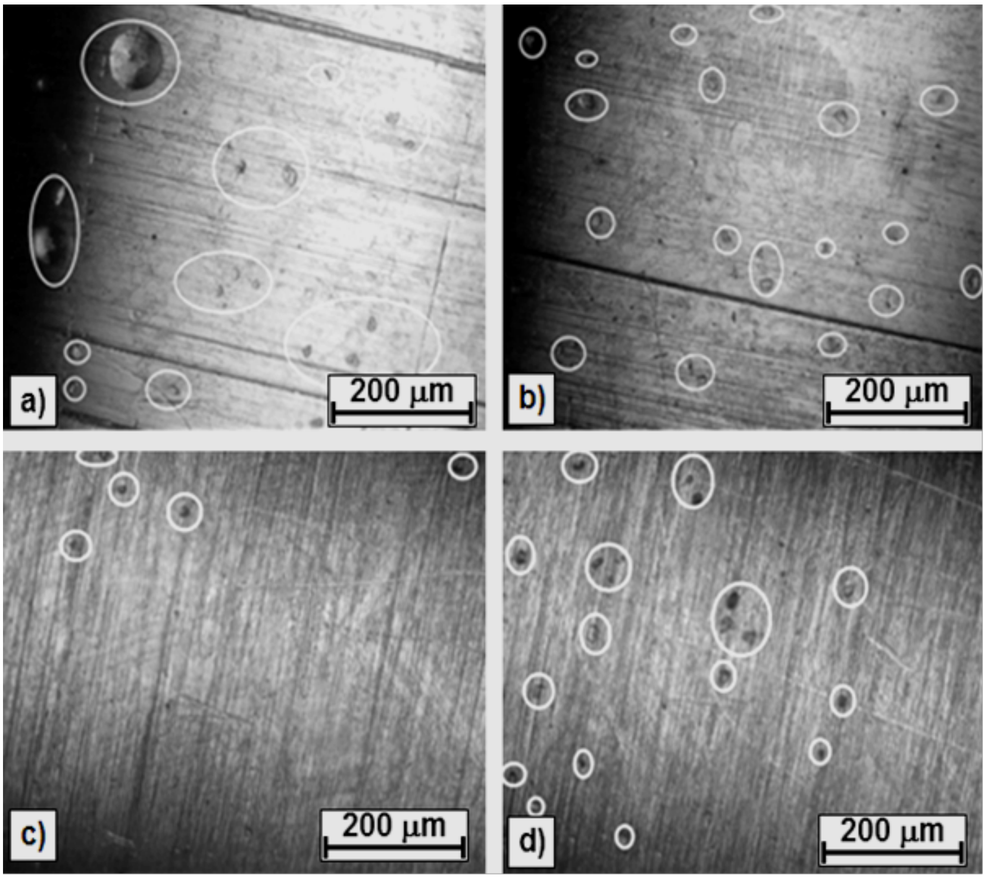

Fig. 10. Examples of surface of the turbocharger shaft after testing (breaks are marked white): a) dry friction, b) lubricated with 15W-40 (new oil), c) lubricated with 0W-30 (overworked oil), and d) lubricated with 5W-30 (overworked oil)

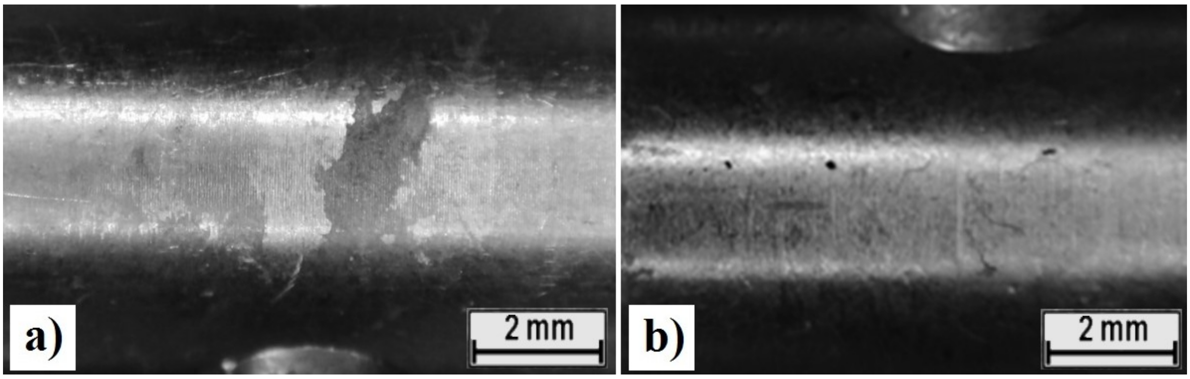

Fig. 11. Examples of surface of the turbocharger slide bearing: a) dry friction and b) lubricated with 5W-30 (overworked oil)

During observing share of surface breaks on the tested surface, the smallest values were obtained for the shaft surface before the test. The highest values were observed for surfaces cooperating with dry friction. In the case of turbocharger shafts tested with lubrication with various oils, it was noted that the lowest wear refers to the use of 0W-30 overworked oil, whereas the highest wear concerns 5W-30 overworked oil. It is interesting that the wear for new 15W-40 oil was higher than for 0W-30 overworked oil. This can be explained by the fact that 15W-40 oil is too viscous and does not provide adequate lubrication conditions.

Table 2

Share of surface breaks on the tested surface

Place of measurement	Share of breaks, %
Surface before testing	0,011
Surface after test - dry friction	3,229
Surface after test - lubricated with 15W-40 (new oil)	0,568
Surface after test - lubricated with 0W-30 (overworked oil)	0,079
Surface after test - lubricated with 5W-30 (overworked oil)	0,748

The average values of the diameters of the breaks were also determined (formula 1). Calculated values are presented in Tab. 3 and Fig. 12.

$$\overline{X_R} = \frac{\overline{X_{D\min}} + \overline{X_{D\max}}}{2} \tag{1}$$

where: $\overline{X_R}$ - average values of the breaks diameters; $\overline{X_{D\min}}$ - average value of the minimum breaks diameters; $\overline{X_{D\max}}$ - average value of the maximum breaks diameters.

Analysis of the results obtained during the examinations was done. It could be noted that the smallest values of the average diameter of the breaks were obtained for the new turbocharger shaft (measurement before the test). The average values of representative breaks increase during the test. Different results were obtained for the various kinds of oil used in the tests.

However, the highest values of the average diameter of the breaks were obtained during measurements for the elements tested under the conditions of dry friction. This proves that lack of lubrication causes catastrophic damage in the bearing of the turbocharger shaft, and this fact causes further damage to this subassembly.

Table 3

Comparison of calculated average diameter of breaks

Place of measurement	$\overline{X_{D\min}}$ average value of the minimum breaks diameters, μm	$\overline{X_{D\max}}$ average value of the maximum breaks diameters, μm	$\overline{X_R}$ average values of the breaks diameters, μm
Surface before testing	1.214	4.875	2.342
Surface after test - dry friction	24.750	31.401	28.075
Surface after test - lubricated with 15W-40 (new oil)	9.324	14.889	11.492
Surface after test - lubricated with 0W-30 (overworked oil)	8.810	14.173	12.107
Surface after test - lubricated with 5W-30 (overworked oil)	10.658	24.173	18.491

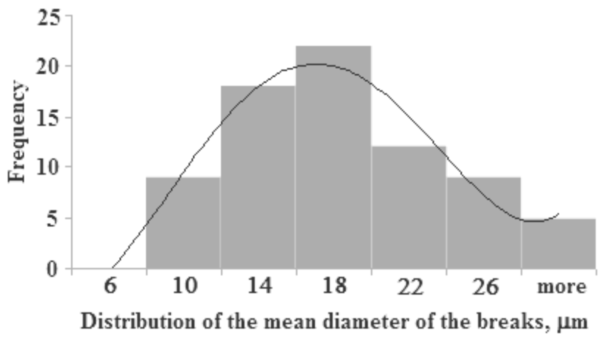

Fig. 12. Example of histogram of average diameters of individual breaks

Among the results obtained for the cases of using various oils for the lubrication of turbocharger bearings, it was noticed that the smallest values of the average diameter of the breaks were obtained for the new oil (15W-40). This oil was characterized by the highest viscosity, but it was a new oil and it did not consist of contaminations.

Among the overworked oils, a smaller average value of the diameter of the breaks was obtained for oil 0W-30 than for oil 5W-30. This indicates better lubricating properties of the oil 0W-30 (lower viscosity).

After analysing the histograms, it can be said that the largest population of breaks diameter is those with diameter of about 18 μm.

5. CONCLUSIONS

The aim of this paper was to determine the effect of different conditions of lubrication (dry friction and lubrication with different kind of oils) on wear of the turbocharger shaft surface.

For investigation, a simplified turbocharger model was constructed (experimental test stand). Tribological tests and quantitative metallographic examinations were carried out.

Different test conditions were set (dry friction and various oils for the lubrication of turbocharger bearings – three different kinds of engine oils – one new and two overworked).

On the basis of this investigation, it is possible to conclude the following:

- there are many conditions that ensure durability of the turbocharger (for example, engine load, temperature of turbocharger and lubrication oil, lubrication oil quality, lubrication oil change, quality of lubrication oil filtration, quality of air filtration, tightness and completeness of intake system and exhaust system);
- the durability of the turbocharger is influenced by both aspects of its use (vehicle user) and its maintenance (mechanic who performs maintenance activities);
- the greatest wear of the surface of the turbocharger shafts was obtained for the condition of dry friction - this proves that it is very important to ensure proper lubrication of this component;
- in the case of tests with lubrication, the highest wear of the surface of the turbocharger shafts was obtained for 5W-30 overworked oil (relatively high viscosity and contaminations in the oil), in the case of lubricating conditions; and
- the case with the smallest wear is not clear (the smallest average diameter of breaks with 15W-40 new oil, and the smallest share of surface breaks on the tested surface with 5W-30 overworked oil).

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