THE INFLUENCE OF THE USE OF DLC COATING ON THE SURFACE OF THE TURBOCHARGER SLIDE BEARING ON ITS OPERATING PARAMETERS

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Abstract

Diamond-like carbon (DLC) coatings are characterized by unique properties (chemical, protective and tribological properties), thanks to which they are characterized by high hardness, resistance to chemical agents and a low coefficient of friction.

The main goal of the article is to determine the working parameters of an internal combustion engine turbocharger after applying DLC coatings on the surfaces of its sliding bearing elements (shaft). Such an application can be considered both in the production of new turbochargers and in the regeneration of already operated turbochargers. The use of a turbocharger has been known in technology for a long time, however, in means of road transport this part is increasingly used in accordance with the idea of downsizing (in the past mainly for compression ignition engines, and now also for spark ignition engines). Currently, DLC layers are used in industry, but their use in the regeneration of parts in means of car transport is rather small.

The article presents the results of testing the turbocharger operating parameters. The tests were carried out using a special test stand. Based on the obtained test results, it can be concluded that the application of the DLC coating on selected surfaces of the turbocharger sliding bearings allows for the change (improvement) of its operating parameters (e.g. increasing the rotational speed of the turbocharger rotor and the air pressure on the charger side at fixed turbine operating parameters).

Keywords: DLC layers, friction, turbochargers, downsizing, automotive industry

1. INTRODUCTION

One of the most important challenges for today's state of technical knowledge are issues related to waste of energy and wear of machine parts. Researches are being carried out on all these fields, both in the laboratory and in the operational field [1-3].

Internal combustion engines are still popular for powering of mode of transportation, but they are affected by changes. These changes are, for example, the reduction of engine displacement and the use of turbocharging (downsizing). This is intended to: reduce fuel consumption, reduce carbon dioxide emissions, reduce emissions of hazardous exhaust gas components. The result is a huge increase in the popularity of supercharging engines using turbochargers. So, despite the fact that turbocharging has been known for years, turbochargers have become indispensable parts of engines and their power systems today. This applies to both compression ignition and spark ignition engines. Turbochargers of internal combustion engines work in very difficult conditions (high temperature, high requirements for bearing lubrication and component cooling). In addition, the way of use the vehicle also has a significant impact on the technical condition of the turbocharger. For example, it is unfavorable to switch off the engine immediately after driving at high speed and with a heavy load on the turbocharger. This causes excessive and accelerated wear of turbocharger parts (for example plain bearings). Another situation is warming up the engine before using of turbocharger due to ensuring proper lubrication conditions for turbocharger bearings. It is also very important to ensure the required amount of oil in the engine and change the engine oil regularly. Generally, it is possible to repair turbochargers by exchanging their moving elements and bearings. It is also possible to extend the life of the components by applying protective layers in the bearing areas (for example on surface of shaft of turbocharger and for bearings). An interesting aspect is the use of DLC layers for this.

This article presents the results of bench tests of selected turbochargers. During the investigations, the rotational speeds of the turbocharger shaft were determined for the established test conditions. The rotational speeds of shafts without DLC coating and shafts with DLC coating were compared. The presence of the DLC coating on the surface of the turbocharger shaft significantly affects its rotational speed.

2. TURBOCHARGERS

Using turbocharger for engine increases its performance (power, torque) typically about 30% in commercial solution in comparison with engine without a turbocharger. Turbocharger is a type of charging device (**Figure 1**). It consists of an exhaust gas turbine that is connected to the charger. The connection is realized by a common shaft and both rotors (turbine rotor, charger rotor) are mounted on a common shaft. Rotors work in their housings. These housings are connected by a central part providing bearing and lubrication [4,5]. 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 which are made inside the housing. This ensures the formation of an oil film.

The higher the rotational speed of the turbocharger shaft (with turbine rotor and with charger rotor), the higher the air pressure at the charger outlet line. The goal is to obtain at the outlet of the charger a stream of air at a pressure greater than atmospheric pressure. Thanks to this, it is possible to feed more fuel to the combustion engine and, consequently, to obtain more power and torque. The high rotational speed of the rotating parts of the turbocharger can be obtained in several ways. One of them is the reduction of friction in the turbocharger slide bearings. This can be achieved by applying a DLC coating to these areas.

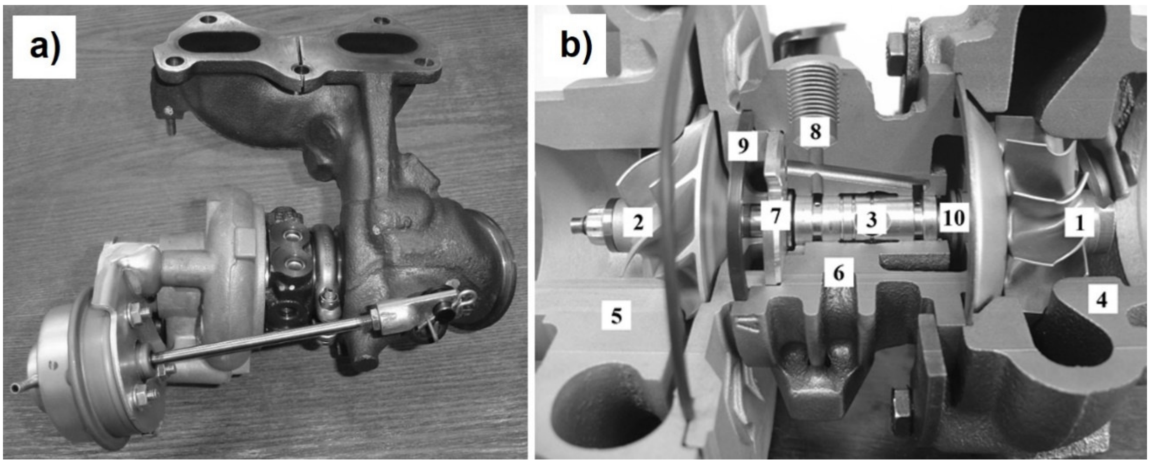

Figure 1 Turbocharger [own study]: a) for passenger car for two cylinder engine with integrated exhaust manifold, b) components: 1-turbine rotor, 2- charger rotor, 3-slide bearing, 4-turbine housing, 5-charger housing, 6-central housing, 7-thrust bearing, 8-oil channel, 9-sealing ring, 10-shaft

The charger is driven by a turbine that uses the kinetic energy of exhaust gases. The turbine therefore uses exhaust gases and it is recovery of lost energy (about 30% of the energy obtained during fuel combustion is carried by exhaust gases). The exhaust gas can propel the turbocharger shaft to revolutions in the very high range (about 200 000 ÷ 300 000 min^{-1}) [6]. Such rotational speed of the rotor ensures correct work of the charger and air compression. Additionally, high temperature of exhaust gas influences on the turbocharger components. Exhaust gases are about 700° C in the case of compression ignition engines and about 1000° C in the case of spark ignition engines. For this reason special materials are used for the construction of components of turbochargers. It means: turbine housing: Ni, Si, Cr, Cu, Mn; turbine rotor: Cr, Fe, Nb, Mo, Ti, Al, C, Ni, Co; charger housing and rotor: Al; shaft: structural steels for thermal improvement; plain bearings: bronze.

3. DLC COATINGS

Carbon based materials are large group of materials which constantly develop. They have a wide range of properties and applications. Coal can take a large number of stable forms, mainly due to its ability to form various hybridized bonds. One of the hardest varieties are DLC coatings (Diamond-Like Carbon). Thin DLC coatings were first made in 1970 [7].These coatings are a combination with very high hardness corresponding to the diamond and with very low friction coefficient corresponding to graphite. It was shown in **Figure 2**. DLC coatings can be deposited using a diverse range of technologies and alloyed with elements such as hydrogen and metals such as chromium. These constituent elements and deposition technique can have a significant impact on the properties and structure of the DLC coating. The use of DLC coatings is one of the most popular way to achieve an abrasion resistant coating. It can be used on the surface of friction pair components.

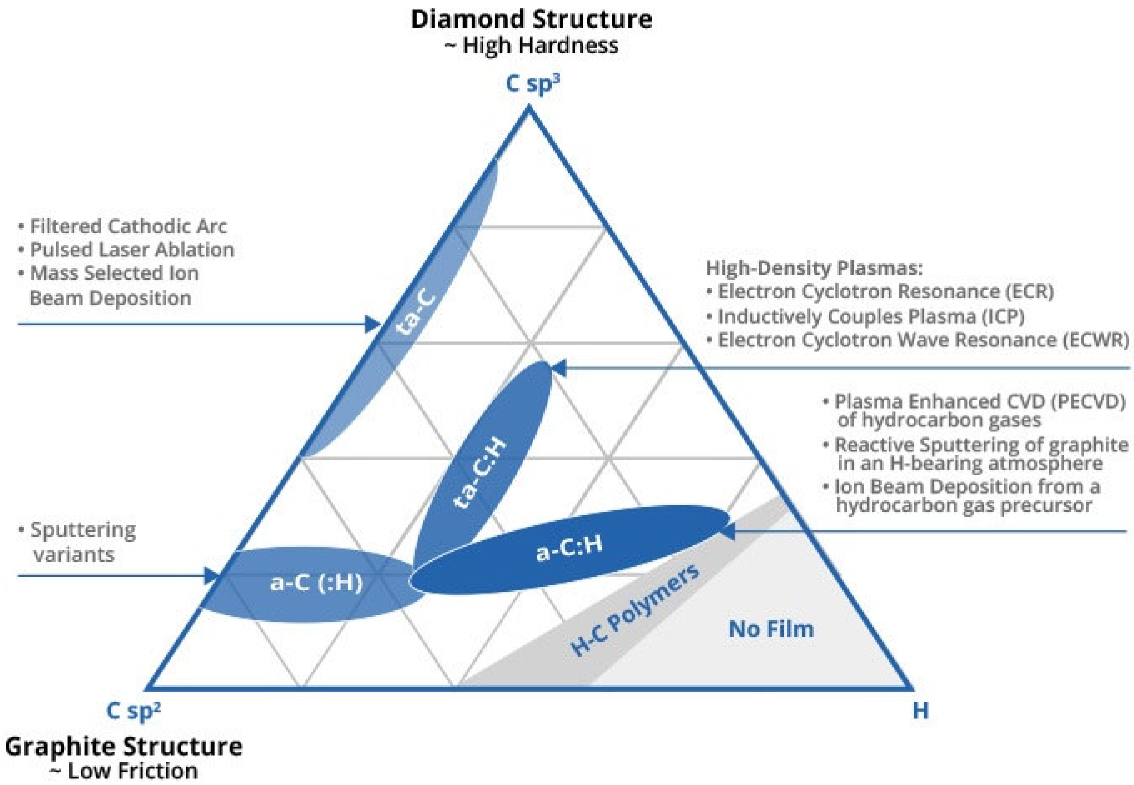

Figure 2 Combination of diamond, graphite and DLC properties, constituent elements and deposition technique [8]

DLC coatings are characterized by passivity, chemical stability and resistance to chemical agents, high hardness, special resistance to abrasive and tribological wear, low value of friction coefficient, thermal conductivity, low coefficient of thermal expansion, high elasticity index and fracture toughness. All these features meet the expectations of the constructors and, to a large extent, solve the problem of seizure the parts. This leads to longer life of the DLC coated parts and significantly reduces the number of machine failures [9]. It is worth mentioning that DLC coatings can be made on the base material in various ways. Examples include sputtering techniques, pulsating laser deposition and the use of ion or plasma beams.

4. TEST STAND AND EXPERIMENTAL PROCEDURE

The planned studies were of comparative nature. The tests were carried out according to the same assumptions and test conditions for all tested turbochargers (with different shafts and turbine rotors). For the purposes of this work, a popular turbocharger model (turbocharger 753420 – GTA1544V) was used. In the turbocharger selected for testing, three different forms of the turbocharger shafts and turbine rotors were used for research purposes (open back and slender shaft, open back and straight shaft, full back and straight shaft – **Figures 3** and **Figure 4, Table 1**). In addition, the results for shafts without DLC coating and shafts with DLC coatings were compared.

The investigations have been carried out with using typically test stand tor testing of turbochargers after its repairs. In addition, a system for regulating the temperature of the turbocharger lubricating oil (oil cooling system) was used in this test stand. It allowed to reconstruct the working conditions (similar to cold start conditions) and lubrication conditions of the turbocharger. Oil viscosity grade 0W30 was used during investigations.

The test stand was powered by compressed air. Compressed air was prepared by a high efficiency screw compressor. The stream of compressed air drove the turbine's rotor. The stream of compressed air drove the turbine wheel. The turbine wheel drove the turbocharger shaft, which drove the charger rotor. This created a high pressure air stream (pressure higher than atmospheric pressure) at the charger outlet line.

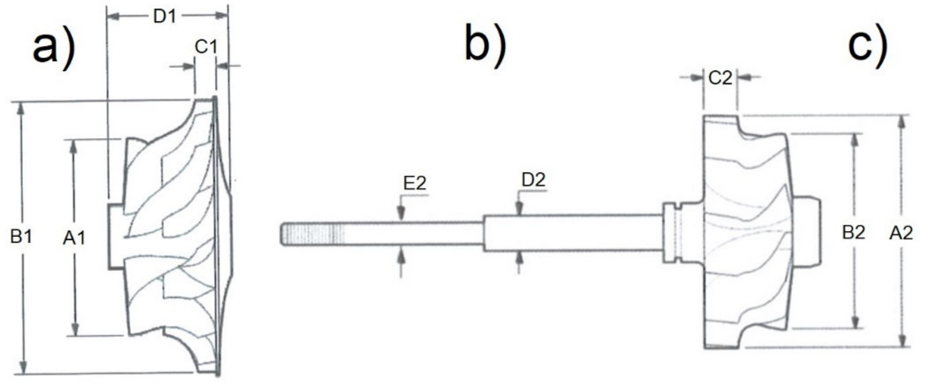

Figure 3 Charger's rotor (a), shaft of turbocharger (b) and turbine's rotor (c) with marked main dimensions [own study]

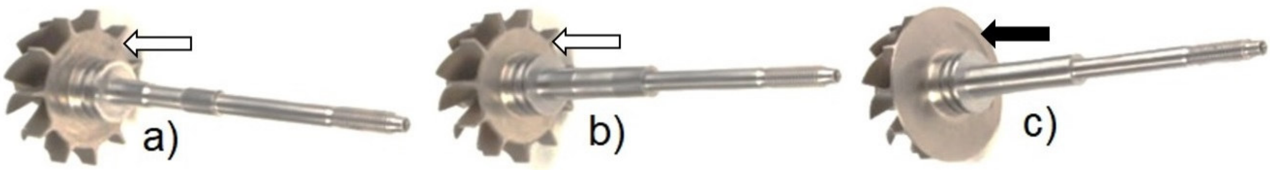

Figure 4 Comparison of different type of shafts and turbine rotors with open back (white arrows) and full back (black arrow) [10]: a) open back and slender shaft, b) open back and straight shaft, c) full back and straight shaft

The rotational speed of the turbocharger shafts was tested for a fixed pressure of compressed air driving the turbocharger and for various turbocharger shafts (shafts with DLC coatings and shafts without DLC coatings). During the investigations oil temperature, oil pressure and atmospheric air 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). The idea of test stand and print screen of test stand display with main data about test were shown in **Figure 5**.

Table 1 Main dimensions of shaft and rotors of turbocharger used in investigations [own study]

Part of turbocharger	Parameter and Value
Charger rotor	A1=33.1 mm; B1=44.0 mm; C1=3.6 mm; D1=24.2 mm
Turbine rotor	A2=39.0 mm; B2=33.2 mm; C2=5.5 mm
Shaft 1 with open turbine back rotor	D2=6.5 mm; E2=5.08 mm
Shaft 2 with open turbine back rotor	D2=7.9 mm; E2=5.08 mm
Shaft 3 with open turbine back rotor	D2=7.9 mm; E2=5.08 mm

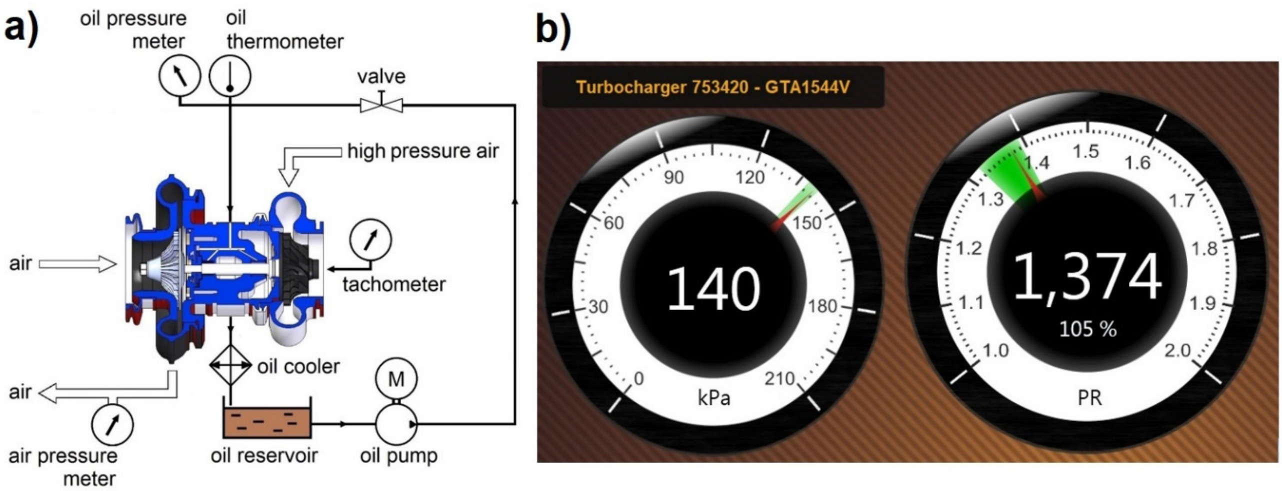

Figure 5 Scheme of the experimental test stand and a fragment of its display screen [own study]

5. INVESTIGATION AND RESULTS

In this work, the analysis of the turbocharger shaft and rotors rotational speed and pressure generated by the turbocharger were presented. Investigations was done on special test stand. The investigations have been carried out with the same assumptions and test conditions. The results show the average and standard deviation of the five tests. Results obtaining during investigations were shown in **Figure 6**.

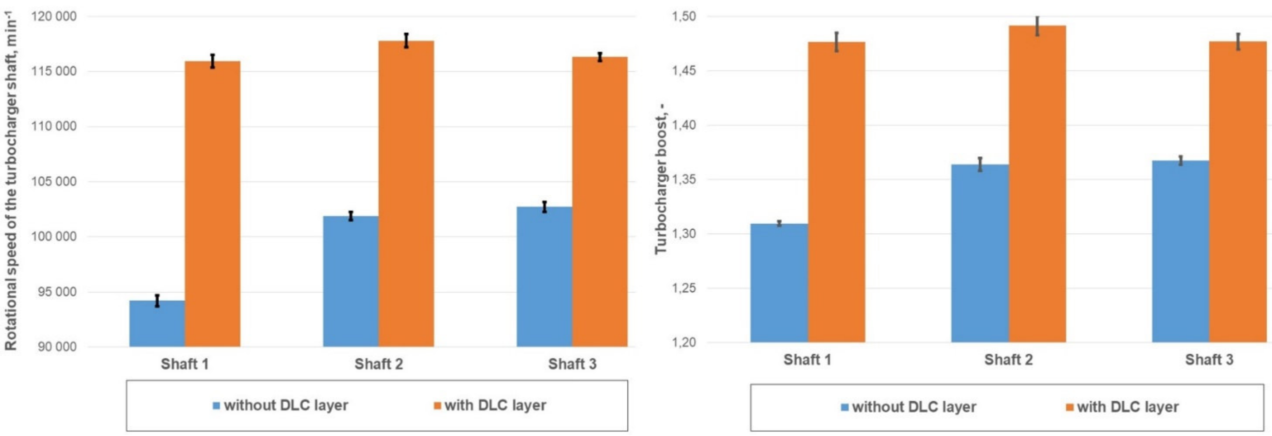

Figure 6 Results obtaining during investigations [own study]

It should be noted that the difference between the average rotational speed of the rotating parts of the tested turbocharger (shaft and rotors) was between 94,208 min^{-1} (for shaft 1) and 102,712 min^{-1} (for shaft 3). These differences resulted from the shape of the turbocharger shafts and the shape of the compressor rotor. After using shafts with DLC coatings in the sliding bearing areas, an increase in rotational speed was observed of the rotating parts of the tested turbocharger. Rotational speed of the rotating parts of the tested turbocharger (shaft and rotors) was between 115,920 min^{-1} (for shaft 1) and 117,792 min^{-1} (for shaft 2). The increase in the value of this parameter was quite significant: by 23.5% for shaft 1, by 15.6% for shaft 2 and by 13.2% for shaft 3. Shaft 1 was characterized by the smallest amount of material, and thus the smallest mass of parts and the lowest inertia and energy consumption of movement - in contrast to roller 3. It is worth emphasizing that the diligence in conducting the research allowed to obtain small values of the standard deviation at the level of about 0.5% (for rollers without DLC coating and for rollers with DLC coating).

In the case of the ratio of boost pressure to atmospheric pressure, the situation was as follows. The difference between the average ratio of boost pressure to atmospheric pressure was between 1.310 (for shaft 1) and 1.368 (for shaft 3). The reasons for this difference are the same as before. After using shafts with DLC coatings in the sliding bearing areas, an increase in the ratio of boost pressure to atmospheric pressure was observed. The ratio of boost pressure to atmospheric pressure of the tested turbocharger was between 1.476 (for shaft 1) and 1.492 (for shaft 2). The increase in the value of this parameter was quite significant: by 12.7% for shaft 1, by 9.4% for shaft 2 and by 8.0% for shaft 3. As before, shaft 1 was characterized by the smallest amount of material, and thus the smallest mass of parts and the lowest inertia and energy consumption of movement - in contrast to roller 3. The diligence in conducting the research allowed to obtain small values of the standard deviation (maximum about 0.6%).

6. CONCLUSION

It was observed that using of DLC coatings influences positively on increasing the rotational speed of the rotating parts of the turbocharger. All operating parameters were identical during the individual tests. It can be concluded that the use of DLC coatings on the sliding surfaces of the shafts of turbochargers reduced the friction in the sliding bearings. This was the case regardless of the design and dimensions of the turbocharger shaft and turbine wheel. This also indicates the possibility of reducing the wear of turbocharger bearings and to obtain higher operating parameters of the internal combustion engine (power, torque) at a relatively low exhaust gas flow from the engine. This will also have a positive impact on reducing energy consumption.

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