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Review Article

Turbocharger Lubrication - Lubricant Behavior and Factors That Cause Turbocharger Failure

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Abstract

This paper is a review of the turbocharger lubrication system and at the same time an attempt to point out and analyze the factors responsible for turbocharger wear, damage and failures. In particular, the conditions under which the lubricant works are presented, from its entrance up to its exit from the turbocharger bearing housing. Additionally, the consequences of failure to comply with the instructions for appropriate turbocharger operation are provided by the various manufacturers. Water cooled turbochargers (for which engine coolant is used), contribute significantly to the reduction of lubricant temperature, in the critical zones of its operation. This is achieved by reducing, the danger of the oil “coking” effect (charred oil residues) or its decomposition, because of high temperature occurring in these zones. Turbochargers shaft support development using semi-floating bush bearings has a significant impact on turbocharger manufacturing cost, as well as on their operational features. Further benefit may be had, when ball bearings are used (usually angular contact bearings are used) for turbocharger shaft support as they provide: a) a reduction of the kinetic friction coefficient, b) reduction of turbocharger lag during turbocharger shaft acceleration from low to high speeds, and c) reduced sealing problems. Regarding the failures that occur in turbochargers, their majority - up to 50% - is caused by problematic lubrication [1]. The rest of the failures are divided between causes related to human factors (such as misuse and inadequate maintenance of a turbocharged vehicle) and external factors such as foreign objects entering either the compressor or turbine housings.

KEYWORDS: turbocharger, bearing, lubrication, floating, semi-floating

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1. INTRODUCTION

The utility of lubricants, except for their basic function to reduce friction between moving surfaces, may be found in the cooling capability they offer to these surfaces too. In most cases, oil works under unfavorable conditions because of the high temperatures that arise due to friction between moving surfaces. Another factor that causes this rise of oil temperature is the migration of heat from the neighboring components which operate at high temperatures. All three components of heat transfer contribute to higher operating temperature in the turbocharger bearing housing: heat conduction between adjacent turbine and bearing housings, as well as compressor and bearing housings; heat convection – directly from the hot casings onto the lubricating oil, and radiative heat transfer primarily from the very hot exhaust turbine housing but, also from the engine depending on the proximity of the turbocharger installation and exhaust manifold to the main engine block. A schematic of the primary heat transfer routes in a turbocharger are indicated in Figure 1. The oil exposure to very high temperatures may cause deterioration of its structure, degradation of its lubricating properties and even, eventually, lubrication failure [2].

As regards the lubrication of the turbochargers, this is a special and at the

same time very important field in which their appropriate and efficient operation is requisite, as is their longevity. The designers of turbochargers insist on ever improved lubrication system designs, which simultaneously provide turbocharger cooling, aiming at a more effective lubrication and cooling process. There are two main areas that must be lubricated, and which have a large temperature difference occurring between them. On one hand, oil passes through the bearing which is located next to the hot turbine housing. Because of the significant heat levels transferred from the turbine housing into the bearing housing (sometimes the exhaust gas temperature exceeds 900°C), oil temperature in this section is increased significantly. On the other hand, the oil passes through the bearing which is located next to the compressor housing. This section is much cooler by comparison to the section next to the turbine housing. Oil temperature is typically between $40\text{-}50^{\circ}\text{C}$ (depending on the environmental conditions in which the turbocharger has to operate). For this reason the use of “synthetic” lubricants is recommended because they behave better in a large temperature fluctuation environment. They also present higher resistance to wear caused by high temperatures than mineral lubricants [1].

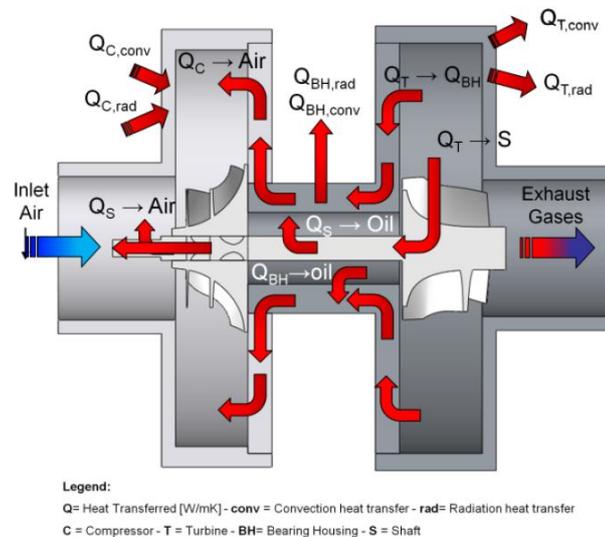


Figure 1: Reduced order heat transfer model in a turbocharger [2]

In spite of this, a significant number of turbochargers get damaged and failures occur due to the lack of appropriate lubrication. The use of improper oil type, the high temperatures that occur in the bearing housing section next to the turbine housing and the turbocharger misuse by the operator, are factors that contribute to the oil coking (Figure 2). As already mentioned oil coking results in a significant amount of charred oil accumulating in the turbocharger bearing section, where it can block the oil flow and therefore, cause turbocharger failure due to the lack of appropriate lubricating oil mass flow rate.

Some of the reasons responsible for oil coking are: a) the supply of oil with inadequate high temperature capability, b) excessive heat in the bearing section, c) extended oil change intervals and d) oil with a wide multiviscosity range [3].



Figure 2: Charred oil residues accumulated in the piston ring region [1]

2. WATER-COOLED TURBOCHARGERS

Many turbocharger manufacturers resort to water cooled turbocharger designs to avoid the coking problem. A water cooled turbocharger has a specially developed circuit that enables flow of the cooling liquid inside the turbocharger bearing housing. The turbocharger cooling circuit is designed in such a manner, that shaft bearings are enclosed, thus removing heat emerging from the outer part of the bearing housing towards the bearings, effectively,

and at the same time dissipating heat from friction generated from the moving parts. On the turbine side of the turbocharger, the danger of lubricant degradation and charring is, also, eradicated by the same means [3].

In case of a great amount of heat being gathered in the turbocharger, caused by a sudden stop of engine operation while working at high load, a small thermostat pump operates, which circulates the cooling liquid towards the turbocharger body to be cooled.

In Figure 3, the lubricant temperature of a water cooled turbocharger is compared to a lubricant-cooled turbocharger, as a function of bearing to volute distance [3].

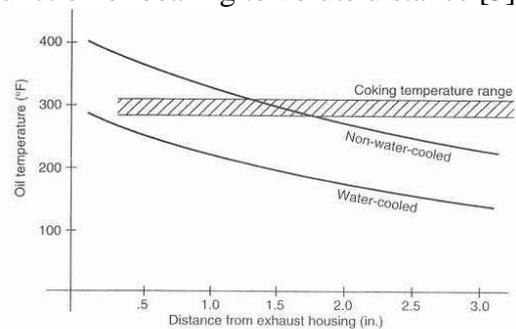


Figure 3: Lubricant temperature of a water cooled turbocharger compared to the lubricant temperature of a non water cooled turbocharger, as a function of bearing exhaust housing distance [3]

3. THE TURBOCHARGER BEARING HOUSING

The bearing housing is located between the turbine and the compressor. There are no significant manufacturing or operating differences between bearing housing designs even if they are manufactured in different sizes and made to meet different applications according to customer needs [4]. The bearing housing encloses the bearings of the turbocharger shaft with the lubrication-cooling circuit, the shaft connecting the turbine rotor and compressor impeller and the lubricant sealing rings.

For low cost turbochargers and up to mid-range power output for automotive applications, roller element bearings are

used. These bearings are located in special placements in the bearing housing bore, between the turbine and the compressor and they are lubricated by the engine lubrication system. Lubricating oil reaches the bearings, from the internal cavities and engravings inside the housing manufactured for this purpose. Under full load, lubricating oil reaches the turbocharger bearings at typical ratings of 2 bar pressure and 1.9 l/min of volume flow rate for conventional turbochargers in this power output range [3]. The bearings and the shaft are designed with adequate tolerances such that the lubricant penetrates between the bearing and the shaft, lubricating the operating surfaces and at the same time reducing friction, while avoiding direct and boundary contact between the surfaces.

After lubricating the bearings, the lubricant is gravity guided towards the engine sump, having lost all the pressure built-up before its entrance to the body of the turbocharger and then towards the bearings. When the lubricant returns to the sump, it is mixed with leaked exhaust gases and compressor driven air which has leaked out from the turbine housing, despite the sealing provisions in the turbocharger (due to thermal expansion and tolerance failure), thus, creating foam. Lubricant foaming is more intense due to shaft oscillation at high shaft rotational speeds, during turbocharger operation at high loads. Foam is viscous and, therefore, the lubricant outlet of the turbocharger bearing housing has bigger dimensions compared to the inlet to assist in oil drainage and thus in keeping with the appropriate oil volume flow rate. This oil pipe ends up in the sump in such a manner that lubricant flow is free and unobstructed by the oil level at the sump.

In the following sections the various types of bearings used in turbochargers are presented in more detail.

3.1. Single Bushing Bearing

These bearings are stable inside the bearing housing bore, simplifying

manufacturing and reducing cost. Lubricating oil forms an oil film between the bearing inner surface and shaft surface, reducing the friction coefficient between the two surfaces and thus avoiding direct-boundary contact between the surfaces (metal to metal contact). Roller element bearings support radial shaft loads but not thrust loads. This is the reason why a thrust bearing is used to support the thrust loads, which is lubricated by the engine lubricating system (Figure 4). This particular bearing configuration causes accelerated wear when shaft resonance occurs during its rotation at high speeds (critical speed). This is the high rotational speed at which the shaft center starts to rotate on its own orbit (in the same direction with shaft rotation) resulting in oil whirling between the bearing and the shaft surfaces. When the shaft reaches its critical speed or when alignment of the shaft is lost, the shaft starts to oscillate resulting in a continuous displacement of its center of rotation inside the lubricating tolerances and the whole assembly starts oscillating between the bearings. For this reason this method has become obsolete.

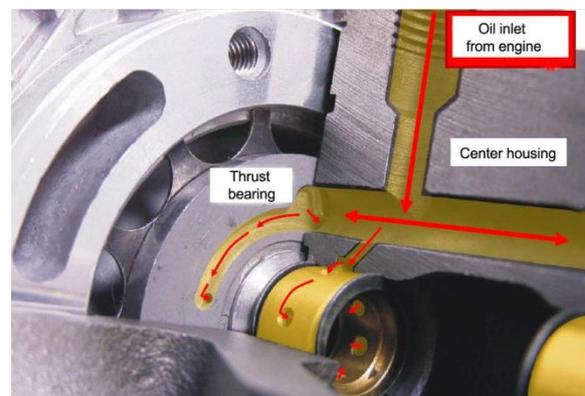


Figure 4: Lubricant flow through the thrust bearing [5]

3.2. Full Floating Bushing Bearings

Full floating bushing bearings are not attached to the turbocharger but there is a tolerance between the bearing and the bearing housing bore surface (Figure 5). In between these two surfaces an oil film is provided by the oil supply system. The lubricant circulates between the shaft and

the bearing (lubricant flows towards the inner clearance through holes drilled on the circumference of the bearing), but also between the outer surface of the bearing and the surface of the bearing housing bore (outer clearance). These bearings are manufactured in such a manner that the inner tolerance (between shaft and bearing) is smaller than the respective outer tolerance (between the bearing and bearing housing bore). During turbocharger operation these bearings are forced by hydrodynamic friction of the lubricant to rotate with the shaft. Rotational speed of the bearings is determined by inner and outer lubricant film resistance forces, acting on the bearing. In theory, bearing rotational speed can reach up to 50 % of the shaft rotational speed. In reality, this speed is smaller, because for a given rotational speed, their speed increases proportionally until it reaches an equilibrium point. Measurements showed that the inner oil film temperature is higher than the outer film temperature, resulting in lubricant viscosity alteration which limits bearing rotational speed [6].

The lubricant film between the bearing and the bearing housing bore functions, also, as a shock absorber (damper); the shocks coming from inaccurate shaft alignment or due to shaft resonance. In full-floating bushing bearings, friction between the shaft and the bearing is reduced by half, resulting in increased turbocharger life as wear between the shaft and the bearing is reduced. Choosing the correct size of tolerance enables optimization of hydrodynamic lubrication, as well as optimization of anti-shock lubricant film behavior. This is the reason why the existing tolerance between the shaft and the bearing is calculated by the turbocharger load carrying capacity, while tolerance between the bearing and the bearing housing bore is calculated so that the anti-shock lubricant film properties are optimized [7].

When the bearing rotates at half the shaft rotational speed, the holes in the bearing circumference, which enable lubricant flow to the inner shaft-bearing

tolerance, are operating as a centrifugal pump resulting in a pressure difference between the inner and the outer clearance formed by the bearing, the shaft and the bearing housing bore, respectively. When this pressure difference occurs, it can exceed the engine lubrication system pressure, causing oil starvation to the inner clearance. As a consequence, bearing and shaft wear can result very quickly due to (dry) boundary contact between the two co-operating surfaces. To avoid this problem, the bearing region which feeds the inner clearance with lubricant has a thinner wall compared to the rest of the bearing and the hole diameters of the lubricant inlet are greater than the wall thickness, reducing significantly the pressure difference. Additionally, another problem appearing in these types of turbocharger is increased wear at the bearing locations in the bearing housing due to their rotation. This problem is partially solved by specially made cast iron cases, while the bearing housing is made of aluminum and the bearing supports are treated with surface hardening. [4].

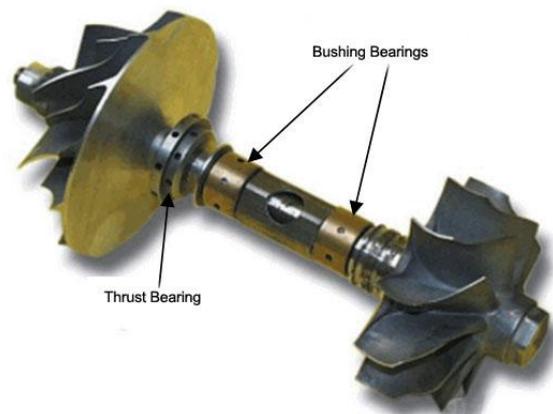


Figure 5: Turbocharger shaft support by the use of floating bushing bearings [8]

3.3. Semi - Floating Bushing Bearings

This most recent turbocharger shaft support method relies on sliding bush bearings, and is achieved by the use of semi-floating bushing bearings (Figure 6). These bearings are attached to the bearing housing and their rotation as well as their axial

motion, are prevented by a flange which is pinned on the end of the bearing. They are only allowed to move perpendicularly to their shaft direction, operating as a damper. The fact that these bearings do not rotate implies that lower oil pressure supply from the engine lubrication system is required compared to full floating bushing bearings. Additionally, when the turbocharger body is manufactured from aluminum, the bearing supports are not required to be treated with surface hardening, resulting in lower manufacturing cost. Measurements of shaft oscillation levels have shown that when single bushing bearings are used for shaft support a 0.001 inch displacement results, whereas, with floating bushing bearings, the shaft displacement is only 0.0002 inches due to their better damping behavior [4].



Figure 6: Different turbocharger bearing types with semi-floating dampering the middle [9]

3.4. Ball Bearing Turbochargers

The use of ball bearings (angular contact ball bearings) in vehicles turbochargers in recent years (Figure 7) is due to the fact that they provide significant advantages over the floating bush bearings. In particular ball bearings provide: a) a lower friction coefficient, b) smaller (oil) tolerances, and c) less oil consumption (because low friction reduces the required amount of oil).

The use of a thrust bearing is not required for turbochargers with ball bearings, because their design features

enable them to support both thrust and radial loads.

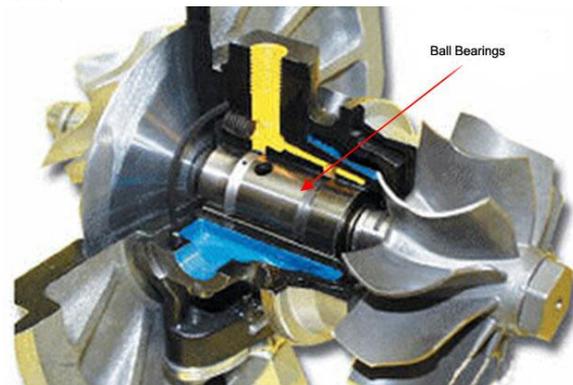


Figure 7: Ball Bearing Turbocharger [10]

One of the main ball bearing advantages is that continuous pressurized oil flow is not necessary, but only a thin oil film is needed, which is created between the rolling elements and the (inner and outer) rings of the bearing. As a consequence, sealing problems are eliminated and at the same time oil consumption by the turbocharger is reduced. In addition, there is a reduction of hydrodynamic friction and internal power consumption. Another feature of turbochargers with ball bearings is that they spool up faster, during an acceleration transient event in the engine, than turbochargers with floating bushing bearings, reducing turbo lag when the engine operates at low speed [11].

Another shaft support method is achieved by the combination of a ball bearing with a bush bearing (hybrid turbocharger). In particular, an angular contact ball bearing is located next to the compressor housing whereas a bush bearing is located next to the turbine housing. In this case, the use of a thrust bearing (located on the turbine side) is required.

In Figure 8, a ball bearing turbocharger is compared to a floating bush bearing turbocharger. In particular in Figure 8a, the spool-up time of a ball bearing turbocharger is compared to the spool-up time of a floating bush bearings turbocharger, as a response to a wide open throttle command. In Figure 8b, the friction torque of a ball bearing turbocharger is compared to the friction torque of a floating

bush bearings turbocharger, as a function of the turbocharger shaft rotating speed. As indicated, in both cases the ball bearings turbocharger exhibits superior performance.

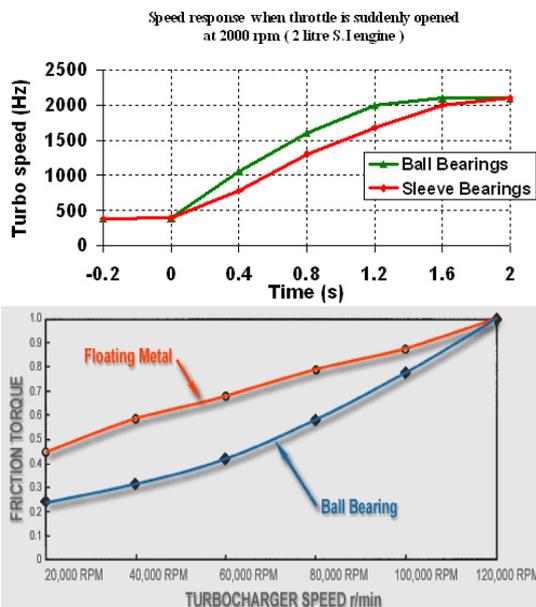


Figure 8. a) spool-up time of a ball bearing turbocharger compared to the spool-up time of a bushing bearing turbocharger [11]
 b) The friction torque of a ball bearing turbocharger is compared to the friction torque of a floating bushing bearing turbocharger [12]

3.5. Turbocharger Sealing Methods

There are various methods which have been used over time to eliminate turbocharger oil leakage (from the bearing housing to the turbine and compressor housings), as well as the elimination of exhaust gas leakage from the turbine housing into the bearing housing. The use of piston rings for sealing (based on the working principle of the internal combustion engine's piston rings) is the most common method used today. One piston ring each, is located both at the compressor and turbine housing ends, in a corresponding groove located on either end of the shaft. These piston rings do not rotate and their ends are located very close to the shaft surface without being in contact with it and with very small tolerance existing between them. In this way, oil leakage from the bearing

housing into the turbine and compressor housings is prevented and exhaust gas leaking from the turbine housing into the bearing housing is prevented as well.

The sealing on the turbine end is achieved relatively easily due to the positive pressure gradient which always occurs between the turbine and bearing housings. Some turbocharger manufacturers use labyrinth type seal on the turbine end, providing more efficient sealing by comparison to single piston ring seals [4].

The sealing on the compressor end is more complex than the sealing on the turbine end, because of the low pressures that sometimes occur in the compressor housing. Some of the reasons causing these low pressures are: a) that air slipstreams occur between compressor housing and compressor impeller backplate, b) pressure drop occurring through the air filter, and c) the low pressure regime occurring at the compressor during non-boost periods, when the engine operates at low or idling speeds (especially in diesel engines). These low pressures cause a vacuum behind the compressor impeller and there is a trend for oil to be sucked from the bearing housing into the compressor housing. This leaked oil then flows through the compressor impeller towards the engine cylinders where it is eventually burned.

One solution to this problem is through the use of the so-called dynamic oil seals. This sealing method uses an oil thrower which is located next to the compressor piston ring and its purpose is to send the oil back in the bearing housing, when it tries to flow into the compressor housing. A number of holes drilled on the circumference of the oil thrower are used for the oil separation from the gas. When the mixture (consisting of oil and gas) reaches this point, oil is drifted because of its gravity and the centrifugal force that occurs, and it is being separated from the gases. After that, it flows through the holes and returns into the bearing housing.

Another sealing method on the compressor end is achieved through the use

of “graphite rings”. The ends of these rings are in touch with the shaft surface due to the force that is applied on them, through springs which are fitted on the compressor housing body. This sealing method provides excellent performance but is not in widespread use because it exhibits increased friction, caused by the contact of the surfaces as well as the increased resistance that appears during shaft rotation [1].

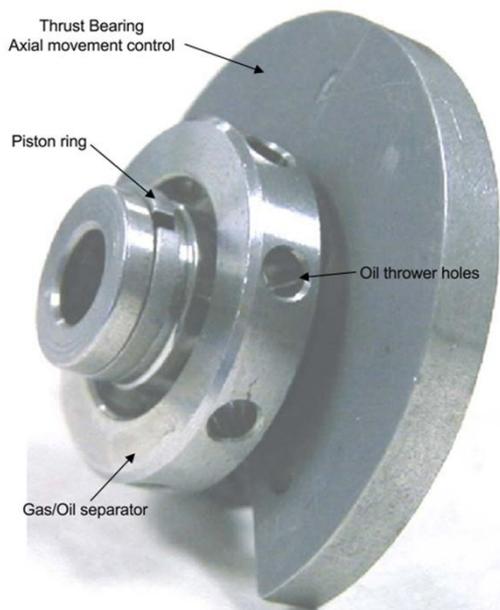


Figure 9: Thrust bearing with a gas/oil separator mechanism [5]

4. TURBOCHARGER FAILURES

Modern metallurgy is used for the manufacturing of turbocharger parts. The use of modern metallurgy is required since turbocharger parts must be constructed or treated, and they must meet manufacturer quality standards. Some of the quality standards that must be met are related to the dimensioning of their parts (dimensional tolerance control) as well as to their operational behavior. Turbocharger parts have very small tolerance ratios after their assembly, and apart from individual alignment they must, also, be aligned as an assembly (rotor system balancing). If any alignment or balancing imperfections are existent in the shaft assembly, vibrations will result during turbocharger operation at

high speed, resulting in a noisy turbocharger and in severe cases, will cause premature bearing failure.

If any irregularity exists after turbocharger parts assembly or during their operation (for instance lack of lubrication or foreign objects entering any of the housings), apart from the eventual partial damage or total failure which can result in the turbocharger due to poor manufacturing quality, will, also, have a detrimental effect on turbocharger efficiency.

4.1. Turbocharger failures due to lack of lubrication

The appropriate quantity of oil flow through the turbocharger, at the right time and at the appropriate pressure, specifies the appropriate turbocharger operation, as well as its long life. Oil is responsible for the following: a) to lubricate the bearings of the turbocharger, b) to provide stabilization to the rotating shaft, as well as to the full floating bearings (behave as a damper) and c) to act as a coolant, preventing in this way the excessive increase of temperature.

When the turbocharger operating conditions change (for example after an increase in rotational speed due to a change in engine load), both the lubrication and cooling demands change (increase) as well. In the case that a momentary interruption of the oil flow through the turbocharger occurs, particularly when the turbocharger operates under high load and high speed, the consequences could be catastrophic for the turbocharger shaft, for its bearings and generally for the whole turbocharger system. The delayed or reduced quantity of oil flow (oil feeding lag) through the turbocharger can be recognized by the discoloration of the shaft or the bearing surfaces at the points of contact (their color turns blue, Figure 9). This is caused by the heat generated at high speed with no lubricant present, as well as due to thermal distress of the materials involved.

The delayed or reduced quantity of oil flow through the turbocharger is mainly

caused by bad operational practice and poor maintenance. An improperly operating oil pump further leads to oil flow with inadequate pressure.

When the engine starts-up, the turbocharger is automatically started as well (exhaust-driven), and it suddenly transits to a high operational load and the rotational speed of the turbocharger tends to reach the maximum allowable speed limit. In this case, no effective amount of oil film exists both on the inside and on the outside clearance of the bearings yet. As a consequence, ineffective lubrication of the moving parts occurs, as well as shaft destabilization. This results in shaft whirling leading to bearing wear.

Other factors that cause this reduced or interrupted oil flow through the turbocharger are the fracture of an oil pipe resulting in oil leakage. If plastic deformation occurs to an oil pipe, it causes the reduction of its diameter, reducing as a consequence, the oil flow towards the turbocharger.

The failure to comply with the recommended oil replacement intervals, given by the manufacturers, results in deterioration of the oil structure. In addition, sludge formation at the internal surfaces of the oil supply pipes, as well as at the circumferential holes of bush bearings. This is more pronounced on the turbine side (because of the hot exhaust environment) and leads to the reduction of the pipe diameter that is equivalent to an oil flow reduction occurring in the turbocharger [4].



Figure 10. Shaft and bearing wear caused by the lack of lubrication. Shaft discoloring (bluing) is noticeable [13].

4.2. Foreign object or dirt presence in the lubricating system

The existence of foreign objects or dirt in the lubricating circuit (contaminated oil) can cause turbocharger wear or failure. These particles drift with and follow the same path as the lubricant flow, increasing in this way the danger to enter or be trapped (if they are small enough) within the inner and outer clearances of the shaft bearings. In such a case, they can cause both bearing and shaft surface engraving wear (Figure 10).

Engraving equals with an increase of either the inner or the outer shaft-bearing clearances, and leads to oil film disorder resulting, consequently, in the increase of shaft vibrations. As a consequence of this increase in vibrations, turbocharger efficiency and its longevity are reduced. In the case that particles are large enough, they can block the internal oil passages, as well as the circumferential holes of the bearings, causing a reduction or interruption of the oil flow through the shaft-bearing clearances. All these can result in an excessive increase of temperature in the bearing housing which can initially lead to melting of the operating parts and thereafter to their welding and eventual turbocharger failure [4].



Figure 11: Shaft and bearing wear caused by contaminated oil [14]

4.3. Foreign Object presence in the turbocharger housings

The existence of foreign objects in the turbocharger housings is another factor that can lead to failure. As regards the compressor housing, when a foreign object enters into it (either because of the lack of air filtering or because of the use of an

inappropriate filter type) while the turbocharger is in operation, it causes damage to the compressor blades (Figure 11). When the object has a significant size, in particular, it causes bending of the compressor blades (mainly at the leading edges) or their fracture. This is more pronounced when the object is of sufficient hardness and while the turbocharger is operating at high speed. In the case that these small particles enter the engine cylinders after travelling down the exit of the compressor through the intake manifold, they can cause serious damage to the moving parts inside the cylinders.

On the turbine side, due to the high thermal stresses under which the engine operates, dislodgement of small particles from engine parts (such as fragments of the exit valves, the piston rings or the spark plug) may occur. When these particles enter the turbine housing, they hit against the tips of the turbine blades, are knocked back into the turbine housing, until their size is reduced to levels such that they are incapable of causing further wear. This kind of wear does not usually cause the turbocharger rotor to lose its alignment and balancing qualities (except for the case where these particles cause a structural blade failure), and it will continue to operate for many hours. In this case, turbocharger failure occurs when one of the turbine blades breaks down and the rotor becomes unbalanced causing in this way the bearings to wear out rather quickly [4].



Figure 12: Foreign object damage [13].

4.4. Turbocharger Overspeeding

Turbocharger overspeeding may occur due to a mismatched engine-turbocharger

combination (comparatively too small turbocharger) in order to reduce turbocharger lag or due to turbocharger aftermarket tuning requirements. Turbocharger overspeeding may lead to turbocharger failure and for this reason it is analysed in this section. The effect of overspeeding is the partial or total wear of the bearing system as well as the distortion of the turbine wheel [4]. Moreover, overspeeding can cause loss of a portion of the turbine blades due to the excessively high centrifugal stresses incurred during such an event (Figure 12). Regarding the damage to the bearing system, it is caused by oil coking as a result of the high temperature build-up in this area, due to overspeeding [15].



Figure 13: (Left) Turbine blade wear due to overspeeding. (Right) Turbine wheel burst due to overspeeding [15].

Another factor which can cause turbocharger overspeeding is the existence of a leakage between the compressor housing and the engine (intake manifold). When a leakage occurs in the intake manifold, a resultant loss of boost pressure can cause the wastegate to malfunction. In such a case, the operation of the turbocharger is aggravated due to the wastegate being programmed to overcome the loss of pressure in the intake manifold by being kept shut. In this way, the amount of exhaust gas flowing through the turbine housing is increased, in contrast to engine operational requirements. This increased exhaust gas flow through the turbine housing, causes rotor overspeed, until the turbocharger compressor flow rate exceeds

the leakage flow rate to reinstate the required volume flow rate of air into the engine. Even a small leakage in the intake manifold, can aggravate turbocharger operation up to 20 % in terms of rotational speed, than the normal operating conditions demand, in order to achieve the desired boost [16].

4.5. Hydrodynamic Lubrication–Failures due to Lubricant Cavitation

In the case of turbochargers equipped with bush bearings, the phenomenon of hydrodynamic lubrication takes place. Hydrodynamic lubrication is achieved by the forced movement of the lubricant existent between two moving surfaces, when these surfaces move towards each other. As regards to flat surface lubrication, hydrodynamic lubrication is achieved when a tilted sliding surface comes closer to another, creating a lubricant wedge. In the case of cylindrical surface lubrication, such as a shaft-bush bearing assembly, hydrodynamic lubrication is achieved by the eccentric rotation of the shaft inside the bush bearing. In this case the lubricant wedge is created in the region of the converged surfaces [17]. The case of cylindrical surface lubrication applies to turbochargers which use bush bearings for their shaft support. When the turbocharger shaft is idling, in particular, its bearing shoulder sits at the lower point of the bearing, in such a manner that a semi-dry contact with the inner bearing surface occurs. As the shaft starts to rotate, for example in reference to Figure 13, in a counterclockwise direction, oil penetrates the two surfaces and a semi-liquid contact is achieved. Due to the small amount of oil which exists at this time between the two surfaces, a partial contact still occurs between them, while the shaft rotates eccentrically. As the shaft speed increases, the amount of oil which is squeezed between the two surfaces is increased too. Shaft surfaces converge at the inner bearing surface because of the eccentric shaft

rotation, causing a reduction of the clearance between them (compared to the clearance of the rest of the circumferential area). The convergence of the two surfaces forces the oil to move into the confined space, creating a lubricant wedge. Within the converging film region, the oil film thickness approaches its minimum value, while the oil pressure rises towards its peak. The partial contact between the two surfaces stops occurring, when a specific rotational speed (called the critical speed) of the shaft is achieved. In this case a full liquid contact (hydrodynamic lubrication) takes place as the oil film increases its load-carrying capacity [18].

In the divergent region of the bearing, the thickness of the oil film increases locally compared to its pressure which drops to ambient or even lower levels. When a significant drop of pressure occurs, lubricant cavitation takes place (Figure 14) [19]. Cavitation is connected with the existence of dissolved gases (air or minute dirt particles) within the lubricant, which are responsible for oil flow separation when the appropriate conditions are present. These dissolved gases either co-exist in the oil mass or are external to it and cavitation is formed because of the negative pressures that sometimes occur (for instance air sucked in to the oil mass) [20]. When oil pressure drops to its vapor pressure point, in particular and in combination with the oil operating temperature rising at the same time, an amount of oil is evaporated. The evaporation of oil generates vapor bubbles trapped in the oil flow, which are subjected to tensile stresses, as well as to high pressure, until their sudden collapse onto the surfaces (vaporous cavitation). Moreover, when the oil pressure becomes lower than the dissolved gas saturation point, air bubbles are generated into the lubricant and cause oil rupture (gaseous cavitation). Gaseous cavitation is more intense when bearings with open ends are used, and an amount of air is sucked into the oil film flow because of the sub-atmospheric pressure occurring in that region. The air bubbles

existent in the oil film, in combination with the high rotational speed of the shaft, cause the formation of foam in the lubricant [19].

Generally, lubricant cavitation occurring in bush bearings reduces their efficiency as well as the oil film load-carrying capacity. Furthermore, lubricant cavitation is responsible to a large degree for wear occurring in the bearings. This is because when the vapor or air bubbles find themselves in a region of high pressure, they collapse. When the bubbles collapse onto the bearing or the shaft surface, high stresses are generated (which can sometimes reach 0.5 GPa) causing wear of the moving surfaces [21].

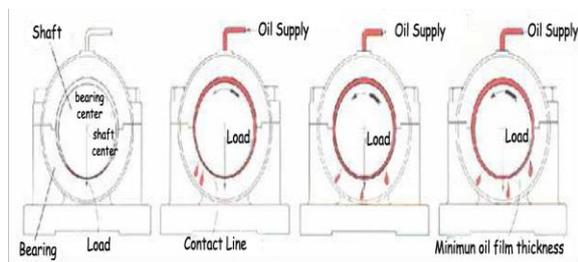


Figure 14: Hydrodynamic Lubrication Process Stages [18].

4.6. Alignment imperfections of the shaft-impeller assembly

After the replacement of a damaged part of the turbocharger, special attention must be paid to the rotor alignment. Alignment imperfections of the rotor, cause an increase of the centrifugal force applied to the rotating parts. The consequence of these conditions is the increase of rotor vibrations which result in uneven bearing wear. Another malfunction which may occur by an unbalanced rotor is the contact of the compressor blades with the internal surface of the volute resulting in a reduction in turbocharger efficiency. In addition to this the vibrations on the shaft are increased and this may lead to structural weakening and possible failure of the compressor impeller blades in addition to the total wear of other rotating parts (especially the bearings), all contributing towards eventual turbocharger failure [1].

4.7. Turbocharger Failure Statistics

In Figure 15 the attribution of causes responsible for turbocharger damage and failure is provided [1]. The values of these statistics and their significance may vary from country to country, depending on the climate – environmental conditions that the turbocharger has to operate in, as well as the type of operational use made from the individual users.

As is shown in Figure 15, 50% of turbocharger failures is related to their lubrication (30% is attributed to the delay of lubricant entrance into the turbocharger and 20% is attributed to the lack of sufficient lubrication). As has been already mentioned in Section 4.1, the delayed or interrupted oil flow through the turbocharger, in combination with the increase in both shaft speed and its load, results in the dry contact of surfaces and consequently, their wear.

Two other causes which lead to turbocharger failures, are (in connection to those previously mentioned): a) lubricant overheating which corresponds to 12% of failures, and b) contaminated lubricant or existence, in general, of dirt particles into the lubricant circuit, which correspond to 13% of failures. Any delay in the feeding of lubricant flow through the bearing clearances means that the amount of oil which already exists into this region, is subject to higher thermal loads (heat transferred by the exhaust gas and heat generated through friction which is not dissipated by sufficient levels of oil flow). These thermal loads cause oil overheating and changes of its viscosity, increasing in this way the danger of oil coking. The phenomenon of oil contamination (except for the causes which are responsible for its creation) becomes more intense as a result of the presence of charred oil residues. These two factors are responsible for 25% of turbochargers failures.

Foreign objects into the turbocharger housings contribute to 3% of all turbochargers failures. The rest of the causes that contribute to turbochargers failure such

as: alignment imperfections (8 %), incorrect rotor-impeller assembly (8 %) and the use of inappropriate spare parts (6%), are attributed to the human error.

An estimated 35% reduction in failures can be achieved, if both the operators of turbocharged vehicles and maintenance personnel, abide more

vigorously by the recommended operating and maintenance practices, respectively. The previous analysis shows that the human factor plays a significant role in turbocharger failures with respect to proper operation and maintenance practices of turbochargers, thus affecting turbocharger longevity as much as environmental factors.

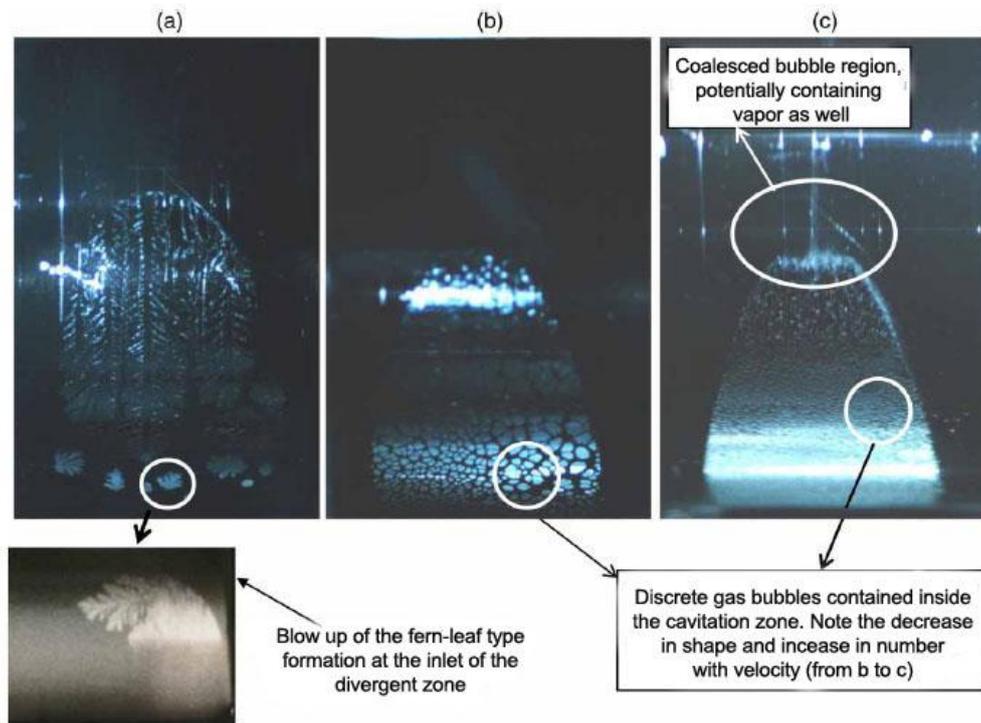


Figure 15: Lubricant cavitation zones [20].

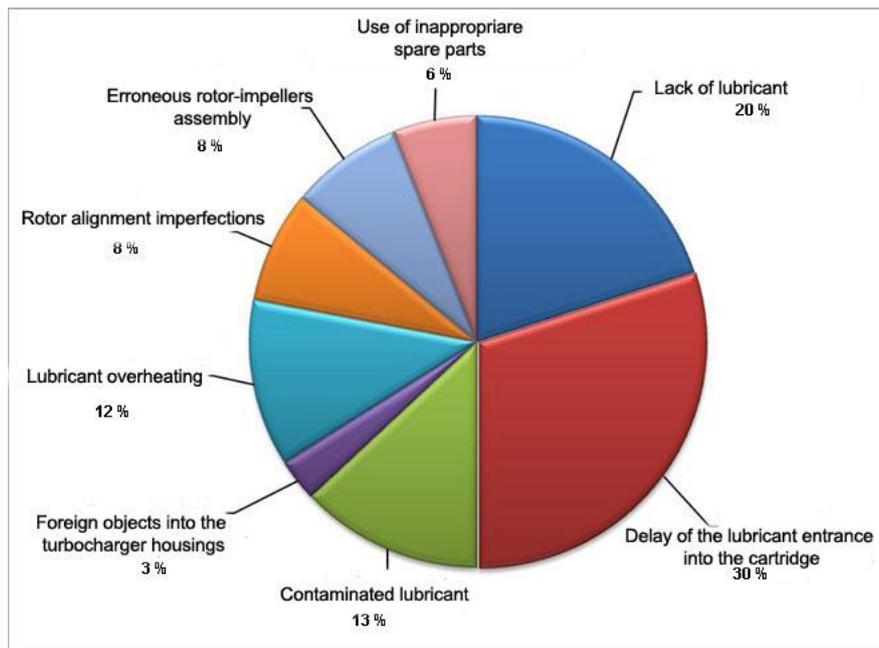


Figure 16: Percentage attribution of the turbochargers failure causes.

5. CONCLUSIONS

Turbochargers are rotordynamic devices which are used to boost engine power to higher levels than equivalent naturally aspirated internal combustion engines. As such they contain, a shaft with an overhung turbine rotor at one end and an overhung compressor impeller at the other. This rotating assembly is capable of very high speeds and careful design of the bearing and lubrication system is required to support such operation.

The selection of bearing type is very important and several such types are available for use in the turbocharger. Among them full floating bushing bearings is the type of bearing that appears to offer more advantages. The reduced friction that these types of bearings offer, contributes to reduced lubricant flow towards the turbocharger, as well as to a higher mechanical efficiency of the turbocharger. This type of bearing, also, reduces manufacturing complexity in achieving effective sealing; in addition, the relative ease of rotation reduces turbocharger lag leading to improved transient engine performance.

Lubrication serves two important functions, namely, the reduction of friction and heat dissipation among adjacent running surfaces in the bearing, shaft and bearing housing. Heat and therefore temperature increase is the result of both friction and heat transfer from the hot exhaust gases running through the turbine housing. Lubrication applied to turbocharger bearings is elastohydrodynamic at the beginning (at low speeds) and the shaft is partially in touch with the inner surface of the bearing (mixed lubrication), while at increased shaft rotational speeds transition to hydrodynamic lubrication occurs which in turn, is responsible for supporting the operating load.

Turbocharger failure is mainly related to problematic lubrication, caused either by mechanical failure to the engine lubrication system or erroneous maintenance-operating

procedures of the turbocharger and the lubrication system. Lubricant cavitation, as well as alignment imperfections of the shaft-impellers assembly, also, contribute in large part to bearing wear.

As statistics suggest, the most significant reason for turbocharger failures is the human factor. Wrong operating procedures (such as sudden transition to high operating engine speed/load) and wrong maintenance procedures (failure to maintain according to turbocharger manufacturer recommendations such as the use of recommended lubricant types and replacement at specific intervals) are the major turbocharger wear and failure causes. A smaller proportion of failures is attributed to material failure and foreign object damage to the impellers housings.

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