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IOP Conf. Series: Materials Science and Engineering **591** (2019) 012020 doi:10.1088/1757-899X/591/1/012020

Scuffing analysis of roller-shoe mechanism after an aggressive test

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Abstract. The roller-shoe assembly is a known and efficient mechanism used for movement transmission in order to obtain mechanical energy. This mechanism is found in high pressure pumps and its role is to change the rotating motion in a translation one. During the running time, some wear types can be identified such as scuffing, corrosion, material removal. Scuffing is the main type of wear appearing in this mechanism. The aim of our paper is to analyse the behaviour of these two components (roller and shoe) over an aggravating test. The main defect is low clearance between components. The roller and shoe assembly is mounted in a diesel fuel pump for test. The test chosen for this experiment is Low Sommerfeld Number. It was stopped after 10% from time set. After visual analysis, it was observed the roller-shoe scuffing. The shoe was analysed and it was observed that the diamond like carbon (DLC) layer is non-conform. In the same pump, the affected components were replaced with new components to be convinced that the wear was caused by low clearance between them correlated to non-conform DLC layer. The test results confirm the reason of scuffing.

1. Introduction

Although nowadays the diesel engines are less and less used on lightweight vehicles for environmental reasons, they are still an important development point in automotive engineering. The diesel engines will continue to represent the core of commercial, transport, agricultural vehicles or other machines that required high power and torque [1]. Considering the rapid development of technology in recent years, pollution legislation has become harsh and the worst factors are being pursued to be removed. The focus is on diesel engines because they are the most polluting, but solutions are being sought to reduce particulate emissions [2].

The performance of diesel engine is directly influenced by injection system, which introduces high-pressure fuel into engine cylinders complying with time and established dosing parameters. The injection system of common rail type plays an important role in reducing the pollutant emissions of the diesel engine and it is chosen as a constructive model by the largest vehicle manufacturers [3]. This is one of the most well-known injection systems ever developed even today. The elements of the common rail system are the high-pressure pump, the injectors, the electronic control unit (ECU), the high-pressure accumulator and the pipes that make the fuel transition possible between them.

In order to comply with legislation and to avoid the dangers created by the noxes eliminated by diesel engines, automotive manufacturers have constantly tried to advance in the development of each component of this system. To this end, the continuous improvement for the common rail system refers to the development of its ability to spray fuel into the engine cylinder as fine as possible, keeping away from the possibility of spreading pollutants into the atmosphere. This may be possible by creating a very high pressure at the outlet of the pump so that the fuel can easily come in through the holes in the injector nozzle [4].

The elements inside the pump that help to create the high pressure are in contact and the damages occurence is inevitable during its functioning. The possible wear types that can be developed are adhesion, fatigue, abrasion, corrosion or impact wear.

The most distructive wear phenomenon that causes total pump dysfunction is the scuffing. Scuffing is a very complex phenomenon because it is affected by many factors and a large number of hypotheses have been proposed in the scientific research. This type of wear appears in many mechanical components with sliding movement and it is determinated by various manifestation [5]. Scuffing, a serious adhesive wear, is the result of combined conditions of lubrication, speeds and pressures of the contact elements, leading to unexpected increase in friction [6]. This complex phenomenon is accompanied by noise, vibration, and operating temperature rising [5].

The injection pump developed scuffing failure due to various causes that may be related to either certain process conditions or to the product manufacturing. Process issues can be caused by materials, treatments, processing, assembling, or even testing. Product issues can be caused by constructive factors (improper clearance, tightening, incorrect dimensioning, deinomination) or exploitation factors (such as overloading, incorrect assembly, incorrect lubrication, inadequate temperature or contamination). The most exposed to scuffing is the roller-shoe mechanism. Usually, the materials of these components are resistant steels with various coatings for friction reduction. Diamond like carbon (DLC) is used such as coating for shoe because its hardness and antifriction properties can be significant increased. Also, the clearance must be very well calculated so as not to cause vibrations or overheating of the components and to ensure a good lubrication. The pressure, speed and temperature are considered to be important factors which can lead to the scuffing of pump elements [5].

Our experimental study focuses on roller-shoe mechanism behaviour during an aggravating test when is low clearance between roller and shoe. We have used the test of Low Sommerfeld Number type because is a static test, all parameters remain constants and the pump is running at high temperature and low speed. Two tests were performed in order to make a comparison. For the first test it was used a pump with components without defects. The second test was performed in the same testing conditions, but with the roller-shoe defects, as we mentioned above, susceptible to cause scuffing. The results highlight that low clearance between roller and shoe correlated with poor adhesion are leading to scuffing.

2. Roller-Shoe mechanism

The pump is the most important component from common rail system because is the one that supplied the high pressure to the rail and further to the injectors. The high pressure pumps have a lot of design variants based on different ways of achieving high pressure. The most used and still manufactured nowadays are those that have movement transmission with piston-tappet and roller-shoe.

Although the high pressure pumps with piston-tappet are very robustness, they cannot reproduce the high performance of the pumps with roller-shoe mechanism and therefore urge major car manufacturers chose this constructive solution. This type of pumps is distinguished by simple construction features, small dimensions, low weight and high performance. They can deliver fuel with pressures of up to 2500 bar at rotational speeds above 5000rpm [7].

The roller-shoe assembly helps to transform the rotation movement from driveshaft in a translation one. Thus, the shoe contacts the piston (a piston return spring is used to avoid the roller lifting off the cam profile) which with pulsating movements is able to create high pressure in the hydraulic head (figure 1).

The roller represents the rolling element in this mechanism [7]. It has a cylindrical shape with a well calculate profile because, when it comes in contact with the running surface, the highest exerted pressure is on the ends. To avoid this, a logarithmic function has been developed to help create a new profile on the cylindrical surface. This logarithmic profile helps to uniformly distribute the exerted pressure on the roller [8]. Considering the working conditions to which the roller is subjected, it must be made of a wear-resistant material that is able to provide stability at high temperatures Also, the increase in hardness can be done with heat treatments.

The shoe is the second element of this mechanism. This is built from a hard material having a good compatibility with the roller's material in order to avoid the scuffing. The shoe is resistant to shocks, crushing and allows the oil to adhere. To have a much higher resistance and to improve the hardness, it is covered with diamond like carbon [9].

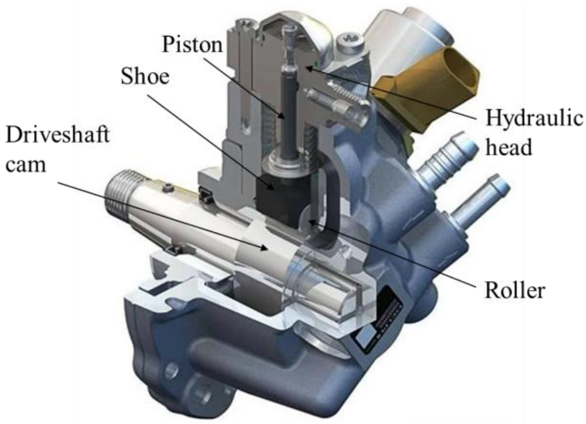

Figure 1. High-pressure pump [7].

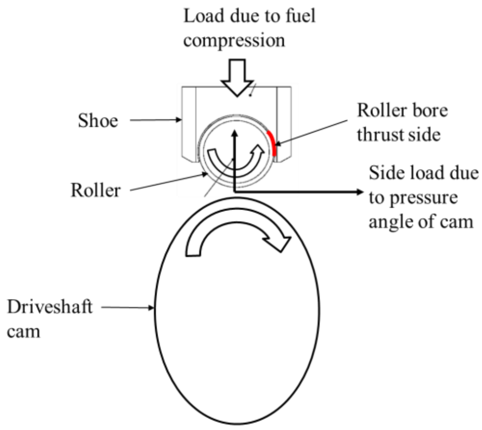

Figure 2. Roller-shoe mechanism.

The roller-shoe mechanism is prone to many types of wear, but the most common is adhesion. Often, due to various incorrectly adjusted factors, the scuffing can appear between these two components and the pump cannot perform its constructive purpose. High-hardness steel is the material of ensemble roller-shoe. Coatings are used to reduce the friction coefficient and also to increase their hardness. During machining process, burns can occur and the coating does not well adhere to the surface. Therefore, during the rolling process, the material removal on the shoe may occur, this meaning the scuffing initiation. Due to the inappropriate working parameters during machining, it is possible to be produced irregularities surfaces, uneven roughness, incorrect material removal, which causes the roller and shoe scuffing. Since these two components are in continuous motion, it is recommended to have a good lubrication.

Lubrication and temperature are two important external factors that need to be monitored to prevent the wear. Insufficient lubrication, incorrect lubricant specification or incorrect lubrication intervals lead to excessive wear. Also, the life of the lubricant can decrease depending on the temperature fluctuations and scuffing can occur at high temperatures, but also at low temperatures.

Other causes of severe wear between roller and shoe are overloading, clearance and contamination. Overloading is caused by inappropriate exploitation. Inappropriate fitting can cause inappropriate loading of the mechanism that transmit the movement to the pump driveshaft. Inappropriate clearance between these two components influences the load distribution, lubricant flow, vibrations, or changes in the temperature of the lubricant. Depending of roller rotation direction (clockwise or anticlockwise) the one of the shoe edge is more predisposed to wear because the pressure is bigger on this side (figure 2). Contamination may be with particles which produce abrasion in the initial phase or with water, where rust can occur. All these situations produce the initiation of wear between roller and shoe and scuffing is often encountered.

3. Experimental methodology

The purpose of our experimental investigation is to study the behaviour of the roller-shoe assembly during an aggravation test, with risk of scuffing. In order to make a comparison, two Low Summerfield Number tests are carried out on high pressure pumps with a roller-shoe transmission mechanism [10]. This test is chosen as it is a good indicator of the fluid film thickness and incorporates all the manufacturer's designed parameters. The roller-shoe relative speed is lower and the lubricant film cannot be continuous.

The first pump tested is a normally assembled pump. The second pump is specially built with a roller-shoe assembly with reduced clearance between roller and shoe. The tests are performed on a special test bench equipped with acquisition boards and transducers capable of transmitting real-time test data. The test fluid is diesel-like properties but non-flammable. The type of test is static, which means that the parameters set at the beginning must be the same throughout the test. For each parameter is set alarm limits on test bench in order to observe the pump behaviour during the test, and if necessary to stop it. Before the testing start, another pump is mounted on the test bench in order to assure the settings. The main parameters are set (motor speed, inlet pressure, return pressure, temperature) and the test bench is running few minutes for test bench calibration.

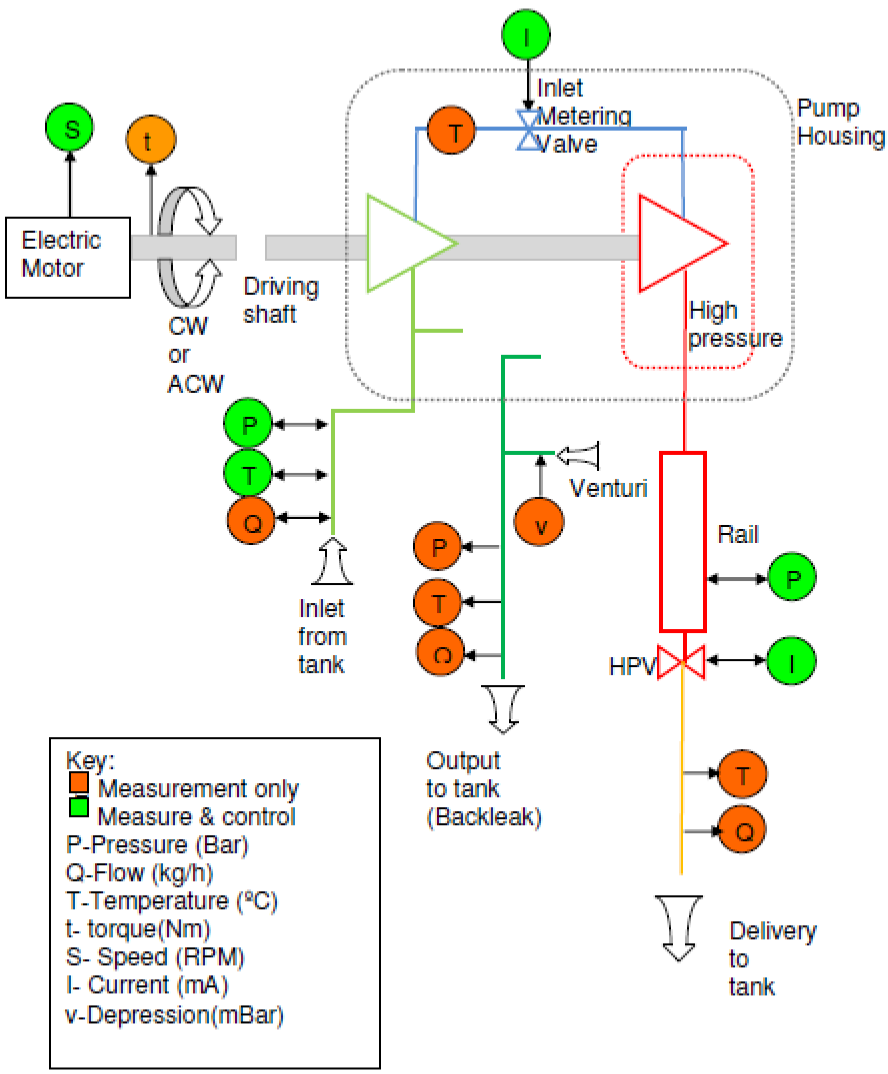

Figure 3. Test Bench – functional scheme.

The pump is driven by an electric motor (clockwise or anticlockwise rotation) and is connected to the test bench at inlet, return and outlet fuel circuit (figure 3). In all these areas the main parameters are monitored with sensors and testing data are taken with data acquisition boards.

4. Results and discussion

The two tests are performed in the same conditions in order to obtain realistic results comparison.

4.1. Test no. 1

The first tested pump is normal assembled and the aim of this test is to observe the normal evolution when there are not defective components. We have performed two types of analyses. The first one refers to the results from the test bench in order to evaluate the parameters during the test. The second one realizes a visual analysis for components after pump disassembly.

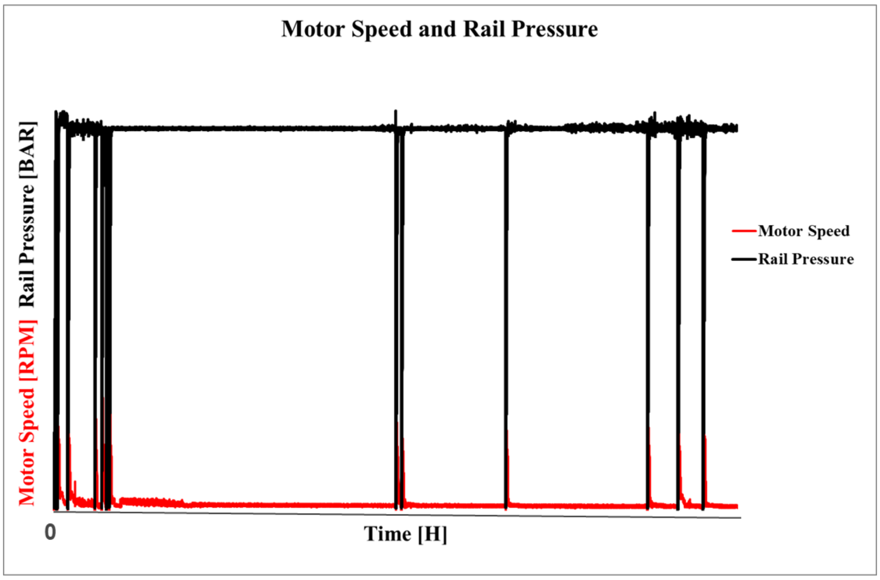

Figure 4. Test No.1 - Motor speed and rail pressure evolution.

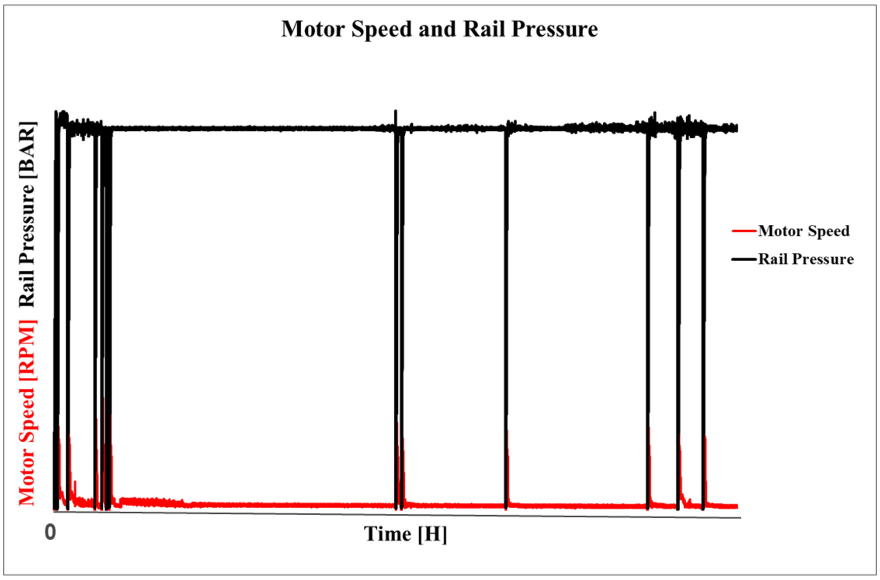

Figure 5. Test No.1 - Temperature evolution.

In these analyses, the numerical values of the above parameters are not important because our immediate interest is to analyse just their evolution. The relevant test parameters are the speed, rail pressure and temperature.

The data analysis (figures 4 and 5) reflect some fluctuations and a few stops, but except these, the rail pressure and motor speed are constant (figure 4). The difference between inlet and back leak (return) temperature (figure 5) is within the limits and the pump has a normal operation.

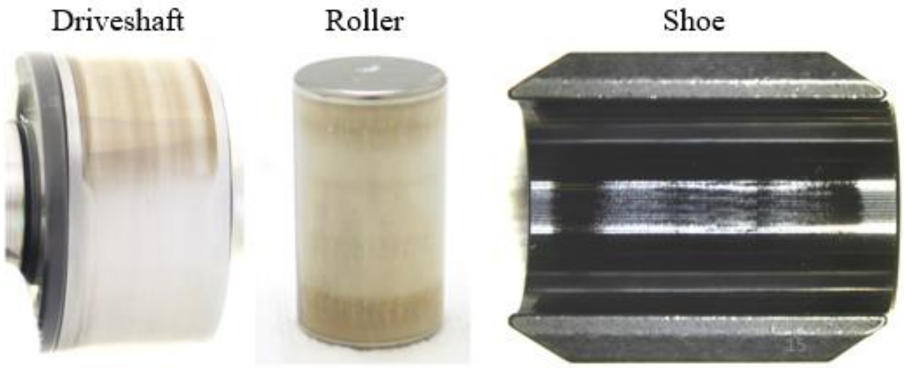

Figure 6. Test no.1 - Visual status of the components of interest.

After the pump is disassembled, it is observed the removal of the superficial layer on the components of interest (figure 6). Also, it is visible the overheating on the shaft due to the test fluid temperature which can reach 120 degrees.

4.2 Test no. 2

The second test is performed with a special assembled pump. The main defect is the low clearance between the components (figure 7). The roller profile (figure 8) and the dimensions of all components are within the manufacturer's imposed limits.

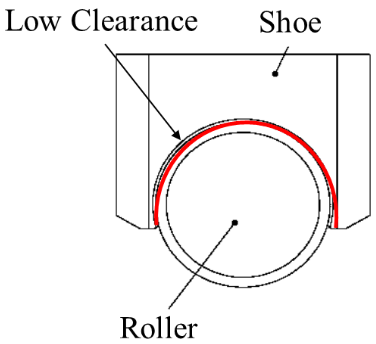

Figure 7. Roller-shoe assembly.

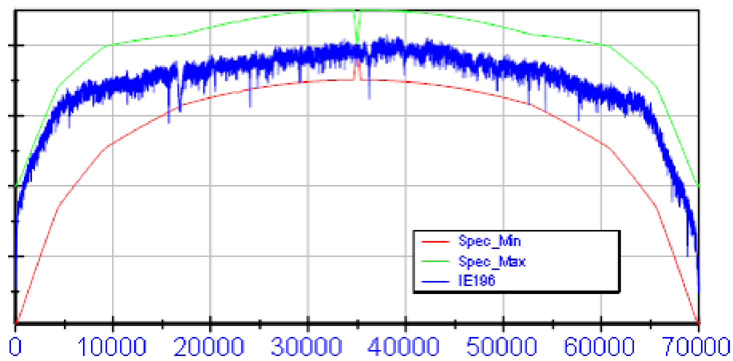

Figure 8. Roller profile – initial condition.

The pump is failed after 10% of the test established time. The test bench was in alarm for two times and the test could not continue. After data analysis it can be observed that the test has two stops and the evolution of testing parameters is abnormal.

The pump cannot deliver the fuel with constant pressure, though the speed seems to be constant (figure 9).

The temperature is quickly absorbed by the material component and cannot reach a high value (figure 10) because the running time is too short.

Considering these parameters evolution, the decision is to stop the test and to check the status of the components.

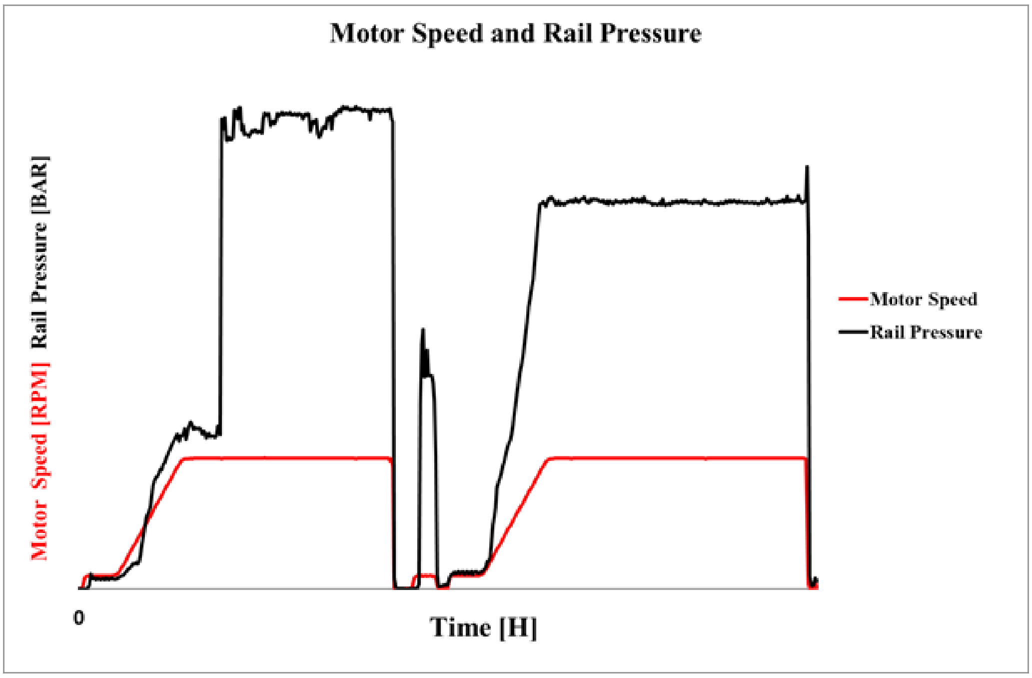

Figure 9. Test no.2 - Motor speed and rail pressure evolution.

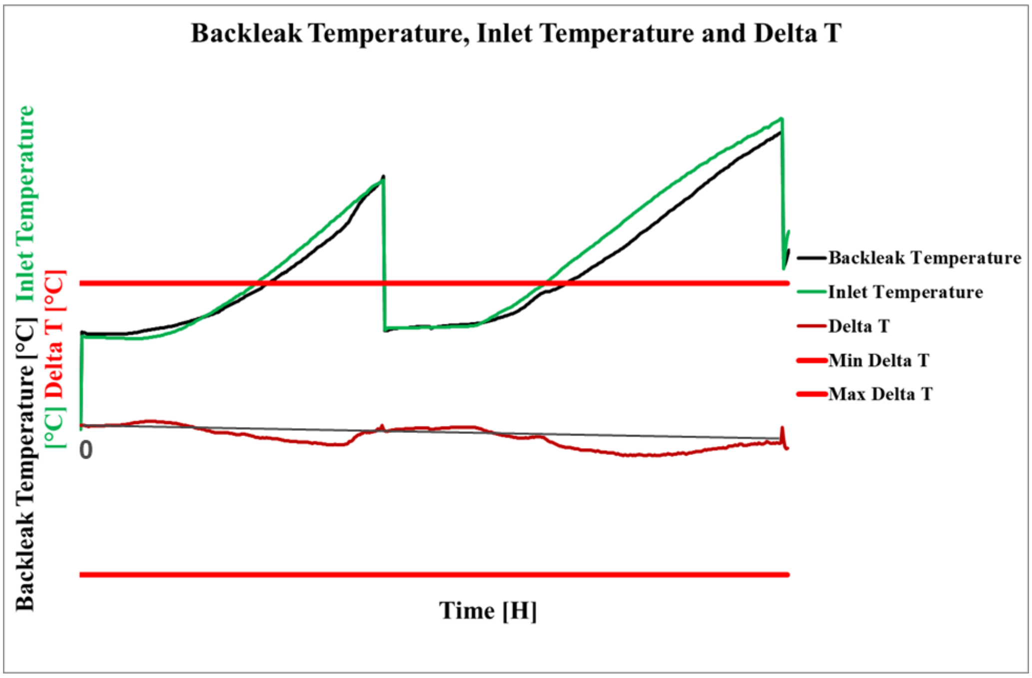

Figure 10. Test no.2 - Temperature evolution.

After the pump disassembly, a big wear is observed on driveshaft and roller-shoe mechanism is subjected to scuffing (figure 11).

The roller profile is not relevant after test because the part is affected by scuffing.

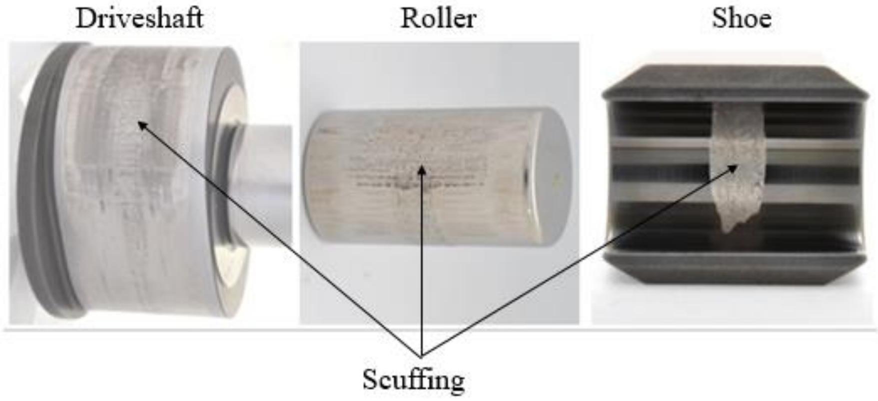

Figure 11. Test no.2 - Visual condition of interest components.

Additional analyses are performed on shoe in order to check the chemical composition and adhesion of diamond like carbon (DLC) layer.

The scanning electron microscope (SEM) material analysis (figure 12) do not reveals cracks, scratches or other possible destructive traces resulting form process machining. Chemical analysis is performed on the two surfaces.

In the affected area (figure 13), it is visible the structure of basic material, with high percent of Fe and C. In non-affected area (figure 14) it is visible the DLC structure. The chemical structure is normal and there was not found contaminants.

DLC layer is checked and it is observed a poor adhesion on the material. The mark left on the DLC layer in unaffected area is marginally accepted (surface no.4 from figure 15) and this may contribute to scuffing appearance.

Figure 12. Affected area – SEM view.

In order to reinforce the tests idea that the simulated defect causes the wear, fresh components (new roller, new shoe and new driveshaft) are mounted in the same pump.

They are subjected to the same test and the result is positive, the pump arriving at the end of test with acceptable wear.

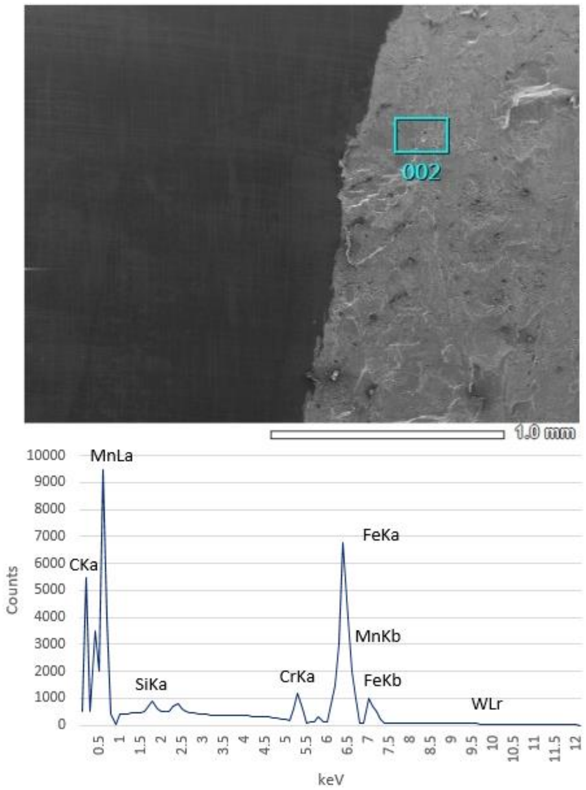

Figure 13. Chemical analysis on affected area.

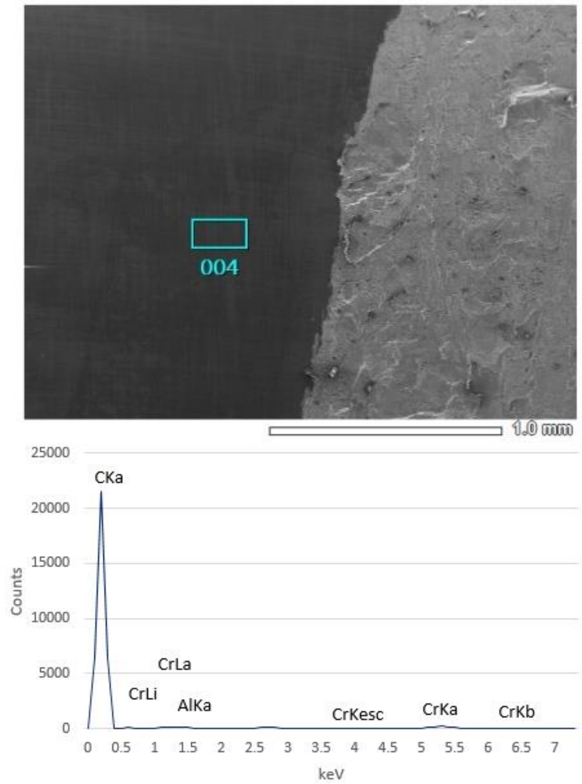

Figure 14. Chemical analysis on non-affected area.

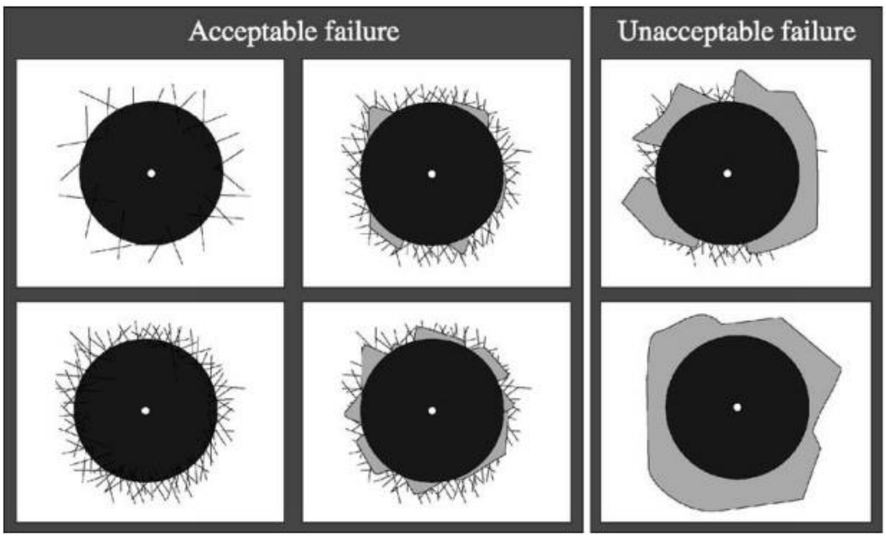

Figure 15. Acceptance criteria for DLC layer after adhesion test [11].

5. Conclusions

Inadequate clearance and poor adhesion of DLC layer are two factors which can be meet very often when we refer at serial production and process automation. The main causes are the time period for machines calibration, inappropriate parameters of machining process or other factors, which can change the structure of basic material and the coating, cannot adhere to the part suface. As we saw, if the DLC layer is non-conform and it is correlated with low clearance, the chance of scuffing appearance is bigger. The Low Somerfield test was chosen because running condition are very aggressive. During the run, the temperature is increased, the material behaviour is changed and new defects can appear. Also, if the running speed is low there is the possibility of the lubricant film breaking. All these conditions are applied in the test above described. The results are suggestive leading to the cause of the pump malfunctioning. This is the scuffing between roller and shoe. Replacing of defective components with fresh components (without defects) confirm us the reason of failure.

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