SSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20230403000499
Original scientific paper

Examination of the Causes for Premature Failure of Mating Surfaces in Smart Injector Actuators

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Abstract: Fuel injector actuators in diesel engines are vital and widely used parts, particularly in hydraulics and fuel injection systems. They largely influence the technical, economic, and environmental quality of an engine. Therefore, it is of utmost importance for actuators to be highly reliable during their service life. Actuator reliability is a distinct feature of their mating surface performance. Due to complex operational conditions, increased surface stress, friction, and environmental impact, mating surfaces are exposed to various types of surface damage, wear, erosion, cavitations, and fatigue. Depending on the quality of production and the conditions they are used in, these damages are often generated much earlier than predicted, which is reflected in the reduction of the actuators' expected life span and reliability. In addition to the above, generated damage triggers the occurrence of other problems with fuel injection systems in diesel engines, resulting in increased fuel consumption and incomplete combustion, together with increased exhaust gas emission. The research conducted here analyzes the working performance of fuel injector actuators in diesel engines in heavy duty vehicles. The research is focused on inspecting the causes that lead to premature damage of mating surfaces.

Keywords: coating; failure; fuel injector actuators in diesel engines; life expectancy; wear

1 INTRODUCTION

Many mechanical structures, different in shape, dimensions, and purpose, have a large number of similar or identical parts, sub-assemblies, or assemblies with the same function, that operate using the same or similar principles. Mechanical structures, including motor vehicles, compressors, and hydraulic pumps that control the rate of flow have similar actuator assemblies. They are vital parts that influence the technical, economic, and environmental quality of mechanical structures that are built in. Therefore, their construction, production, and maintenance require permanent development.

Theoretical and experimental research, as well as product experience and monitoring of premature vehicle failures, showed that the life expectancy of actuators mating surfaces is significantly less than expected/designed and that also varies largely. Most common reasons for reduced life expectancy are inadequately applied final subsurface layers coatings, inaccurate geometry of mating surfaces, and mechanical impurities contained in the fuel.

Among the papers that presented damage of fuel injection system assemblies, two papers stand out. The first paper analyzed fuel injection nozzle damage from the aspect of material fatigue, [1], and the second one, [2], analyzed cam plate damage with a focus on pitting wear in the rolling element surface and cam plate. Both papers are based on the analysis of the condition of the material without coating, which is analyzed in detail herein. This paper maintains the continuity of mating surface damage analysis with the application of the new coatings for protection against wear, whereas it has elements of wear mentioned in the previous papers [1, 2].

In order to better inspect the possible causes for the large variations in the life expectancy of fuel injector actuators, their performance was analyzed in operational vehicle conditions. State of mating surfaces in new actuators vs. used actuators is the main indicator of working performance. Parameters such as hardness, roughness, geometric accuracy, and adhesion strength of mating surfaces are the main indicators of the quality manufacture of actuators. In order to observe the impact quality the manufacture has on actuators life expectancy, we analyzed the condition of mating surfaces in new actuators vs. used ones. This research shows that there is a significant difference in the life expectancy of actuators that had been used in the same or similar conditions. Contact surfaces (mating surfaces) of actuators that had been used in operational conditions were analyzed using the SEM electron microscope photomicrographs. This analysis showed that a non-compact coating and uneven film thickness on the area of contact and side areas of mating surfaces have the greatest influence on large variations in the life expectancy of actuators, both in the used and new actuators.

2 ANALYSIS OF THE POSSIBLE DAMAGES OF ACTUATOR MATING SURFACES

High product quality requirements in modern mechanical structures impose the need for high-quality mating surfaces. Therefore, technological procedures used for modifying mating surfaces are constantly improved. Their performance depends on the physical and mechanical properties of the materials in the thin surface layer, stress-related working conditions, load frequency, and the environment, i.e. fluids types and mechanical impurities.

Actuators are used for fine regulation of fuel flow in the injection system. The main indicator of actuator quality is the susceptibility of its composite mating surfaces to the wear. This susceptibility is measured using the fluid pressure drop gradient. In high susceptibility, a mating surface tends to wear pressure drop gradient increases. A smaller pressure drop gradient indicates lower mating surface susceptibility to wear.

Pressure drop gradient testing can be analyzed in two ways. It can be done by measuring the pressure drop time in a certain range or by measuring the return amount of the test liquid per 1000 injection cycles. Based on both of these parameters, the condition of actuator composite mating surfaces can be monitored, which is described in details in [3]. The actuator composite mating surfaces wear resistance depends on technological and operational conditions. During the final formation of mating surfaces, residual stresses may be generated in the subsurface layer which may change the shape of crystal lattice. Furthermore, geometric accuracy can be violated in terms of tolerance length measures, shape, mutual position, and roughness of mating surfaces. These irregularities have a significant impact on the working performance of mating surfaces in operational conditions.

Mating surfaces are not ideally smooth. Actual mating surfaces consist of micro roughness (micro bumps) different in shape and size, so the load is transferred from one area to another via the tops of the bumps. Therefore, the actual surface pressure has a different value at each point of contact, Fig. 1. In operational conditions, the micro geometry of mating surfaces is constantly changing. The bumps created upon manufacture are replaced by new micro roughness (micro bumps), so that each new contact is made on slightly deformed mating surfaces. Under the influence of working load, the actual surface stress distribution on mating surfaces can be approximated by the mean distribution flow or the Hertzian contact stress. In addition to the normal stress-surface pressure, tangential stress is generated in the subsurface layer of the mating surfaces. It peaks at a certain depth in the subsurface layer.

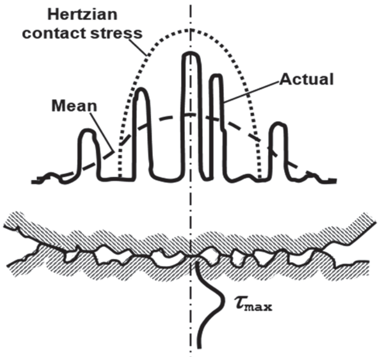

Figure 1 Contact stress

When the maximum tangential stress reaches its critical value, initial crack forms in the subsurface layer. Due to the periodically reverse stress-surface pressure, the initial crack gradually expands and eventually reaches the mating surface. Destruction products, tiny flakes of material, are formed then, and tiny pits form on mating surfaces, Fig. 2. This type of mating surface destruction is called pitting [2].

In order to reduce this type of destruction, actuator mating surfaces are made with high-quality surface roughness. If present in the area of contact, impurities from the fuel are pressed into the subsurface layer. High surface stresses are produced in those areas and, over time, this leads to fatigue crack initiation in the subsurface layer. Corrosion can occur around the pits that are formed, as the protection (coating-metallization) has been removed on those areas of the mating surface. Furthermore, the impurities and/or products of destruction small flakes of material prevent the mating surfaces from being completely sealed. Fuel with mechanical impurities under five micrometers circulates between the mating surfaces, through the formed slit gap, corresponding to the maximum permeability of the input filter. When passing through such a gap, mechanical impurities carried by the flow of fuel circulating on the mating surfaces cause surface damage in the form of erosion. To reduce the impact of mechanical impurities on the actuator mating surface damage in a circulating fluid, appropriate pre-filters (separators) and fine filters with a permeability of less than five micrometers are placed. However, small particles that break away from the coating due to poor adhesion strength or pitting corrosion products and other types of surface damage may also generate mechanical impurities in the circulating fluid. In addition to different types of wear and tear, non-compactness of the coating was observed in one group of actuators, whereas uneven coating thickness on the front and side areas was observed in the other group. Analysis conducted showed that the degree of aforementioned defects in actuator manufacture, combined with impurities in the fuel, has the greatest impact on the differences in the life expectancy of actuator mating surfaces.

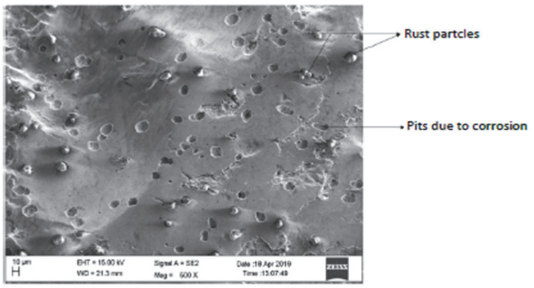

Figure 2 Rust particles and cam plate pitting caused by surface corrosion [2]

3 OPERATING CONDITIONS OF THE ANALYZED SMART INJECTORS

For the purpose of this research, 60 smart injectors were monitored to analyze the operation of smart injectors in operational conditions. Fig. 3 shows a fuel injection system that consists of a smart injector, rail and high-pressure pump, [4].

The basic criterion for evaluating the service life of used actuator was the pressure drop of the fuel flowing through the injector, caused by leakage due to damage of mating surfaces of a smart injector actuator. The pressure sensor, which is an integral part of the pressure accumulator, detects the difference between the pressure set and pressure reached as protection and puts the system into failure mode, which leads to limited engine performance.

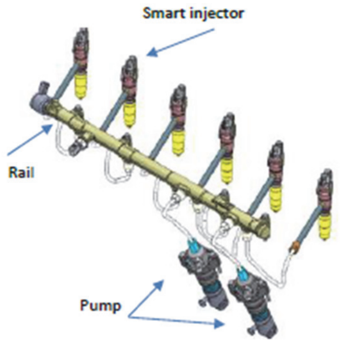

Figure 3 Fuel injection system

In some actuators, life expectancy was significantly shorter than designed, far below one million kilometers, which is equivalent to 4 - 6 years of use. Only three smart injector actuators had a life expectancy of less than one year. Some actuators were still in use after one million kilometers, without any mating surface damage, making this paper interesting to analyze.

4 EXPERIMENTAL RESEARCH

As part of the experimental research, damages on the mating surfaces were considered based on microstructure analysis, roughness, and hardness. The following microscopes were used to analyze the damage generated on the actuator mating surfaces:

- Stereo microscope - LEICA M205A.
- Digital microscope color camera LEICA DFC295.
- SEM - JEOL JMS-6610LV.

Detailed analysis of damaged mating surfaces, as well as the microstructure of previously cut and prepared intermediate plate, was performed with the above-specified microscopes.

The intermediate plate was cut off with Erosimat emulsion in order to prevent heat and residual stresses. Upon analyzing the damage, the stereo microscope was used first, followed by the digital microscope color camera and the SEM microscope.

4.1 Chemical Composition, Roughness, and Hardness of Mating Surfaces

The Belec Compact Port spectrometer was used to analyze the chemical composition of the actuator mating surface material. The obtained results are shown in Fig. 4.

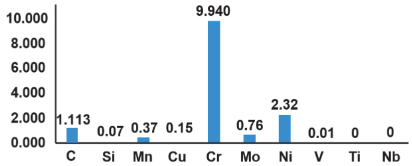

Figure 4 The results of the analysis of the chemical composition of the actuator mating surface material

MarWin
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10:44:30
Inspector:
Part: prizma1
Drawing n°:
Machining operation:
Signature:
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Measuring instrument:	MarTalk
Drive unit:	SD26
Probe:	BFW A 10-45-2/90 1504/13

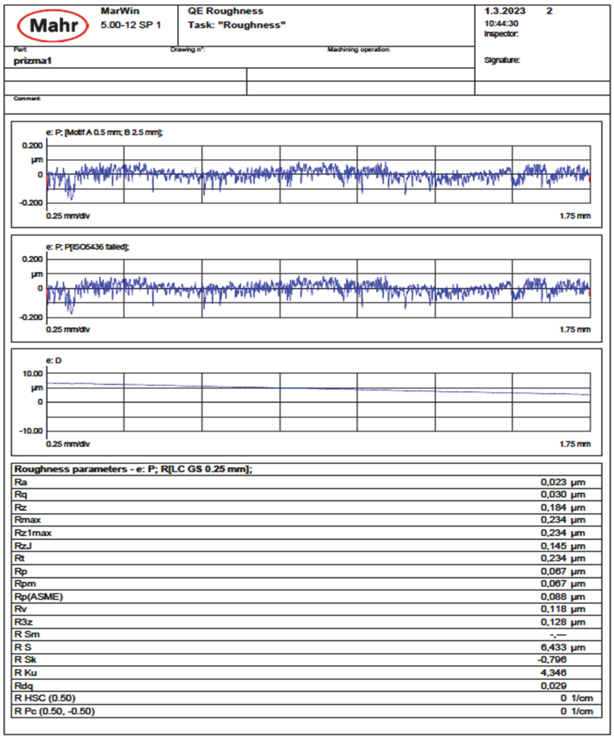
Lt:	1.75 mm
Ls:	2.50 µm
VB:	+/-250.0 µm
Vt:	0.10 mm/s
Points:	3499

Figure 5 Graphic of micro roughness

Based on the results obtained, it may be concluded that it is made of carbon martensitic stainless steel. The closest steel grade per the DIN standard is X91CrMoV18.

The DLC coating roughness directly depends on the ion impingement energy, whose value below 50 eV produces a rough surface, whereas if the threshold is increased, the roughness shall sharply decline [5]. The most common DLC coating roughness value does not exceed 0.3 µm, whilst in our case, $R_{\max}$ is 0.234 µm, as shown in Fig. 5 and Fig. 6.

The volumetric hardness of the intermediate plate material and the actuator pin is 63 HRC, measured using the Insize ISH-RD200 hardness tester. The DLC coating surface hardness was approximately 22.38 GPa (2282 HV) [6].



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QE Roughness
Task: "Roughness"
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Inspector:
Part: prizma1
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Roughness parameters - e: P; R[LC GS 0.25 mm];	
Ra	0,023 µm
Rq	0,030 µm
Rz	0,184 µm
Rmax	0,234 µm
Rz1max	0,234 µm
RzJ	0,145 µm
Rt	0,234 µm
Rp	0,067 µm
Rpm	0,067 µm
Rp(ASME)	0,088 µm
Rv	0,118 µm
R3z	0,128 µm
R Sm	-,—
R S	6,433 µm
R Sk	-0,796
R Ku	4,346
Rdq	0,029
R HSC (0.50)	0 1/cm
R Pc (0.50, -0.50)	0 1/cm

Figure 6 Micro roughness results

5 RESULTS AND DISCUSSION

5.1 Visual Observation and Macro Fractographic Study

Upon visual inspection, it can be concluded that all actuators are damaged only at the point of contact between the actuator and the intermediate plate, i.e., the central hole and area between flat surface and hole, Fig. 7 and Fig. 8. It was determined that there is a lack of coating on the surface layer between the hole and the flat surface, as shown in Fig. 7.

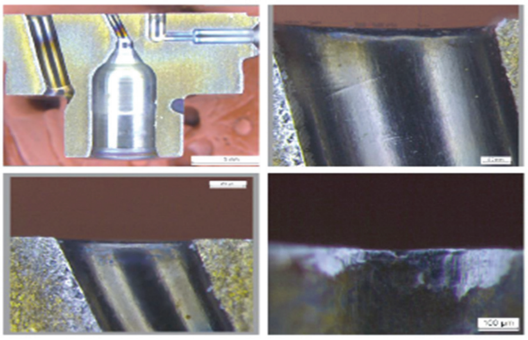

Figure 7 Macro and microphotographs of injector actuator cross-section

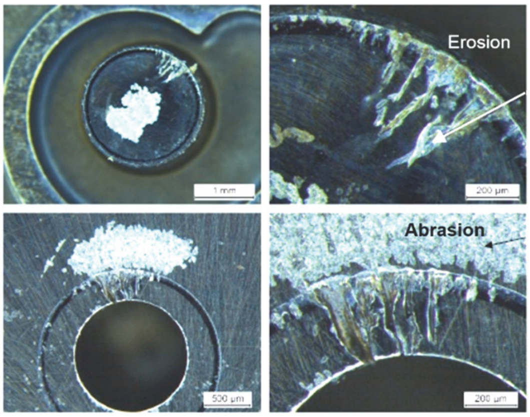

Figure 8 Stereo microscope image of the damage

5.2 Microstructure Characterization

Tempered martensite, as used in the manufacture of the actuator and the intermediate plate is characterized by its needle-shaped features, which can be inferred from the microstructure analyzed by SEM, and shown in different sizes in Fig. 9.

5.3 Microfractography Analysis

Stereo microscope image analysis shows abrasive wear as the most common cause of damage to mating surfaces (Fig. 8), assuming that the particle size is smaller in diameter than the gap at the moment fluid is injected. Also, in addition to abrasive wear, the analysis showed erosion that can be caused by the fluid flow, which often occurs on the turbine blades and centrifugal pumps. Additionally, the resulting damage can be superimposed if the fluid carries abrasive particles.

Furthermore, cavitations caused by high pressure in the injector actuator may widen the canal on the mating surface of the actuator pin and the intermediate plate. Crack initiation leads to the formation of the canal that wears away the seal between the intermediate plate and the actuator pin, [1].

5.4 Fracture Profile

Fig. 10 clearly shows coating on the external flat surface and a 30.5 μm lack of coating on the lateral surface. Low bond strength between the base material and the coating resulted in the coating wear off. The loss of coating is additionally affected by the border surface created at the sample corner, i.e. between the outer and side surfaces, Fig. 11. This border surface may contribute to the formation of cracks on the coating surface [7].

Fig. 12 and Fig. 13 show faults in the coating, and two different layers on the outer side of the sample. Thickness of the coating on the outer sample side is approx. 3.4 μm, whereas it is not uniform on the lateral side and ranges from 7 to 7.5 μm. Delamination between the layers of the coating on the outer surface is observed (Fig. 12 and Fig. 13). Delamination was not observed on the side. Fig. 10 shows a loss in layer 2 at the transition from the outer side to the lateral side of the sample. The cause of the observed faults (poor adhesion, delamination) may be found in an inadequate process of applying the coating, and/or it is linked to the operational conditions. Base material has martensite uniform structure throughout the entire surface.

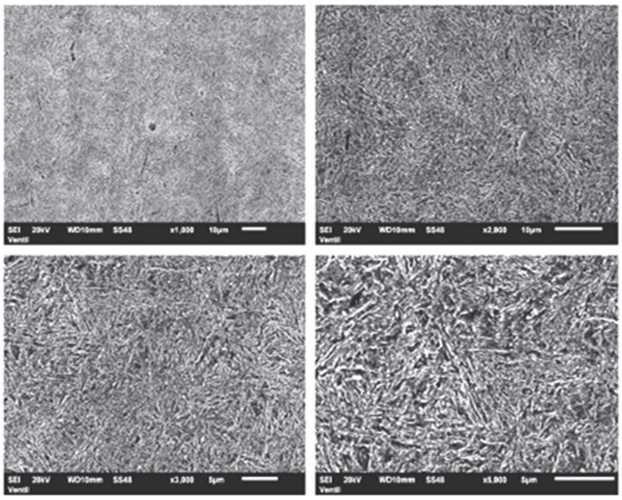

Figure 9 Actuator material microstructure

5.5 Fracture Factors and Recommendations

One of the additional factors of the rapid decline in actuator working performance is damage to the coating of actuator pin (the actuator pin and the intermediate plate have a mating surface where the damage was observed). These damages were generated on several new actuators, as shown in Fig. 17.

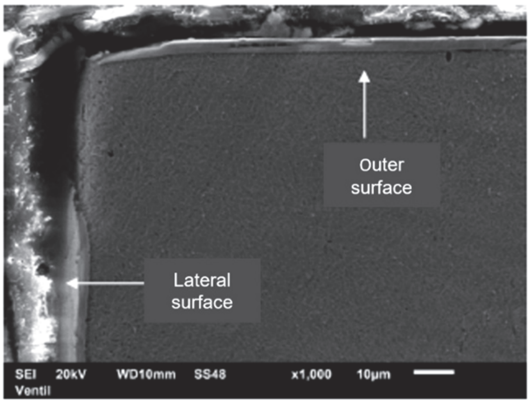

Figure 10 Coating surface

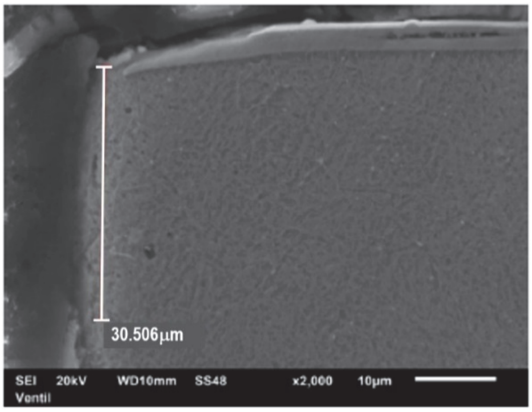

Figure 11 The loss of the coating

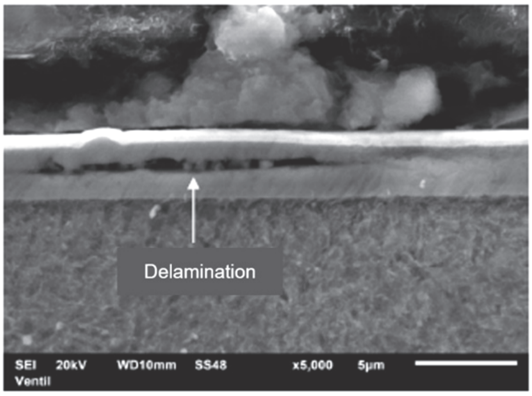

Figure 12 Delamination in coating

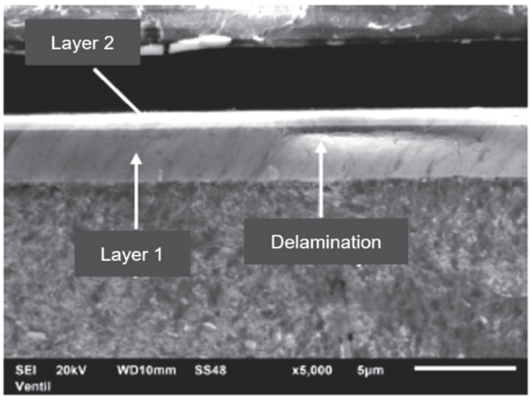

Figure 13 Faults in coating

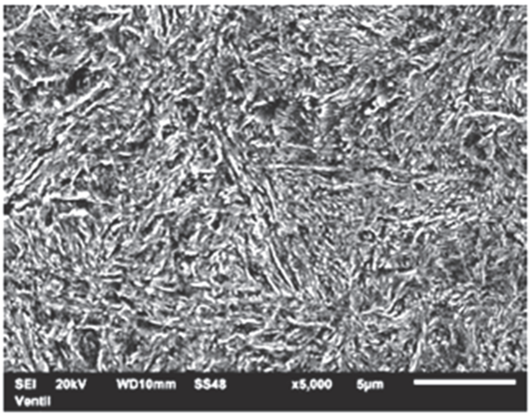

Figure 14 Base material microstructure

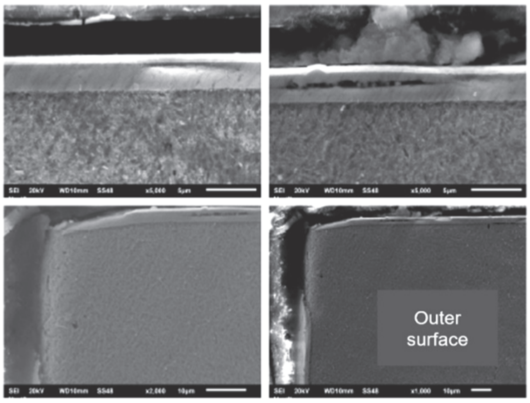

Figure 15 SEM photomicrographs without dimension values

Damage to the coating indicates inadequately coated pins. Under operating conditions, rapid damage to mating surfaces occurs due to abrasion and erosion caused by small particles of the detached coating. In further use, this damage causes performance reduction in actuators and smart injectors.

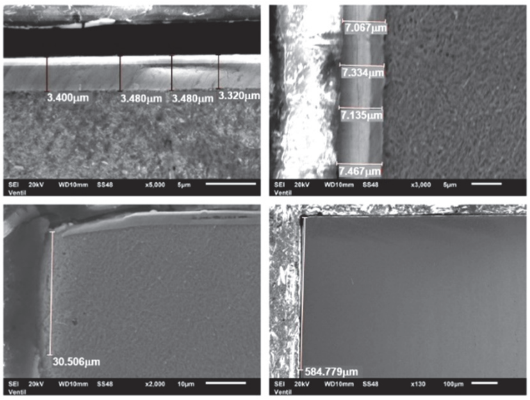

Figure 16 SEM photomicrograph with coating thickness dimensions

DLC coating 1.8 ÷ 2.17 µm thick with 22.2 ÷ 25.7 GPa surface hardness, evenly applied to the mating surface, did not meet the quality requirements [8, 9].

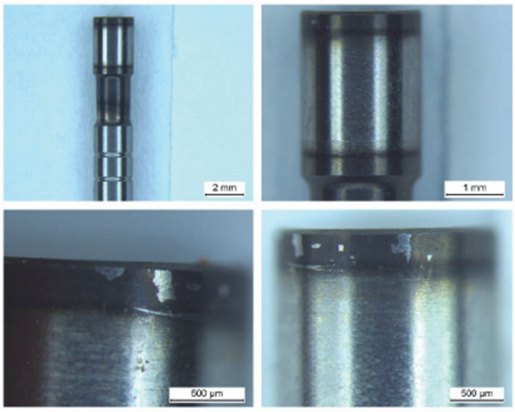

Figure 17 Actuator pin damage

6 CONCLUSION

The analysis conducted in this paper showed that the variation in the life expectancy of diesel engine actuator mating surfaces in heavy-duty vehicles was predominantly caused by the defects on mating surfaces due to manufacture process. These defects, combined with mechanical impurities in the circulating fluid led to mating surface damage.

Low bond strength between the base material and coating on the actuator pin side explains the separation of small pieces of the coating which continue to circulate inside the actuator. When fluids containing detached coating pieces reach the contact area of mating surfaces, sealing becomes incomplete, which impacts technical, economic and environmental performance of smart injectors.

In order to reduce the variation of the life expectancy of actuator mating surfaces, it is necessary to increase control during the formation of the subsurface layer in mating surfaces. In addition to the above, it is necessary to increase control of the operating conditions in terms of the quality of circulating fluid and purifier, as well as the purifier replacement frequency.

The assumption that the main cause of the damage to the actuator pin mating surface and the intermediate plate are impurities in the fluid caused by poor filtration was eliminated.

The analysis conducted for this paper showed the shortcomings of DLC coating due to manufacture. Because of the poor-quality coating, mating surfaces in smart injectors have had a significantly shorter service life than designed. Damaged injectors must be replaced with new ones, or regenerated/ repaired in good quality and put back into operation, which is a far more economical and environmentally friendly option.

7 REFERENCES

[1] Xu, X. L. & Yu, Z. (2021). Failure analysis of a truck diesel engine injector nozzle-valve. *Engineering Failure Analysis*, *120*, 105084. https://doi.org/10.1016/j.engfailanal.2020.105084

[2] Deulgaonkar, V. R., Pawar, K., Kudle, P., Raverkar, A., & Raut, A. (2019). Failure analysis of fuel pumps used for diesel engines in transport. *Engineering Failure Analysis*, *105*, 1267. https://doi.org/10.1016/j.engfailanal.2019.07.048

[3] Cha, S. C., Park, H. J., Lee, J. H., Ko, K. Y., & Shin, C. H. (2020). Exploring the Effectiveness of a Complex Coating Technique for Use the Smallest Parts of Advanced Powertrain Fuel System. *International Journal of Automotive Technology*, *21*, 1976-3832. https://doi.org/10.1007/s12239-020-0064-1

[4] Jankovic, D. (2012). *Predlog novog koncepta ispitivanja sistema ubrizgavanja goriva* 38th ed., Univerzitet u Beogradu-Mašinski Fakultet, 3.4-3.46.

[5] (n.d.). Delphi Technologies note DT5402 (EN).

[6] Peng, X., Barber, Z., & Clyne, T. (2001). Surface roughness of diamond-like carbon films prepared using various techniques. *Surface and Coatings Technology*, *138*, 23-32. https://doi.org/10.1016/S0257-8972(00)01139-7

[7] Bounif, K., Abbadi, M., Nouari, M., & Selvam, R. (2021). A numerical approach for crack-induced damage in tungsten carbide cutting tools during machining. *Engineering Failure Analysis*, *128*(105617). https://doi.org/10.1016/j.engfailanal.2021.105617

[8] Bounif, K., Abbadi, M., & Nouari, M. (2022). The effect of diamond like carbon coating on the wear resistance at dry sliding conditions. *Materials Research Express*, *9*(116504). https://doi.org/10.1088/2053-1591/ac9bd4

[9] Djoufack, M. H., Maya, U., Brogelmann, T., & Bobzin, K. (2015). Wear behavior of hydrogenated DLC in a pin-on-disc model test under lubrication with different diesel fuel types. *Tribology International*, *92*, 12-20. https://doi.org/10.1016/j.triboint.2015.05.020

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