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Failure analysis of high pressure fuel pump on piston aircraft engine

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Abstract. High Pressure Pump (HPP) failure leads to a sudden fuel cut off, during the training flight. To investigate the root cause of HPP failure, two more aged fuel pump (TSN 600h), from the same flight academy, was received. The failed pump and aged pumps were disassembled and analyzed by optical microscope (OM), scanning electron microscope (SEM) and metallographic analysis. Results showed that the metallographic technology of the three pumps were the same. Foreign debris found in the failed fuel pump stuck one plunger. At next revolution the rotor was pushing hard against the follower plate causing a sheared plunger and cylinder. Subsequent fragments leads to the other two plungers' failure. Due to more and more debris, other parts of the pump fail as a secondary failure. Friction or stuck marks in the failed pump and the other two aged pumps indicated that it is more likely to have axial scratches in operation base Z. This operation base is close to desert.

1. Introduction

High Pressure Pumps (HPP) are widely used on high speed common rail diesel engines, in the automobile industry. HPP increases fuel pressure and provides fuel atomization power [1-2]. The injection pressure is usually higher than 160MPa, in order to reduce the exhaust emission. Most of these pumps are plunger pumps, and use diesel fuel for lubrication. HPP is also a critical part on reciprocating aviation piston engine [3-4]. Since jet fuel is the most widely used fuel in aviation industry, reciprocating aviation piston engine has to burn jet fuel instead of diesel. The lubrication performance of jet fuel is not as good as diesel. Low lubrication performance makes the pump more sensitive to the foreign particles. HPP failure will endanger the flight safety.

Here is a real case. During the training flight, the engine power dropped to 1% in 1 second, then increased to 27% abruptly, and finally back to 2%. The pilot tried to adjust the power setting but with no feedback. So forced landing process was executed and the aircraft landed safely. HPP failed with obvious external damage. To investigate the root causes of the HPP failure, two more aged fuel pump (TSN 600h), with the same model number of the failed pump was received. The failed pump referred to herein as 'Failed Pump'. The aged pump operated at the same Base Z referred to herein as 'Aged Pump Z'. The aged pump operated at a different Base Y referred to herein as 'Aged Pump Y'. Base Y was located at central China with moist climate, and Base Z was located at northwest China, close to desert.



2. Analysis and discussion

2.1. Failed pump disassembling

The schematic diagram of inner structure was shown in Figure 1. The three plungers are driven by a rotor shaft. The cycle of fuel absorption and discharge is completed in one rotation. The failed pump block had an obvious damage area, as shown in Figure 1 (red arrow). Obvious bulge and deformation can be seen in the other two corresponding position (blue arrow). Internal damages were shown in Figure 2b. The plunger plate and the metal clamp ring (metal ring), can't be found in the failed pump. In addition, all the plungers were stuck in the cylinders. Lots of crushed metal particles were found inside the block.

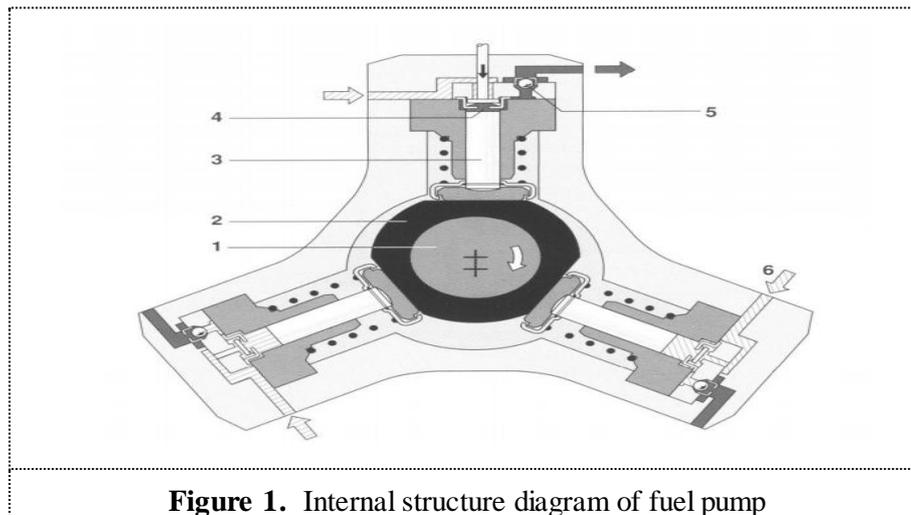


Figure 1. Internal structure diagram of fuel pump

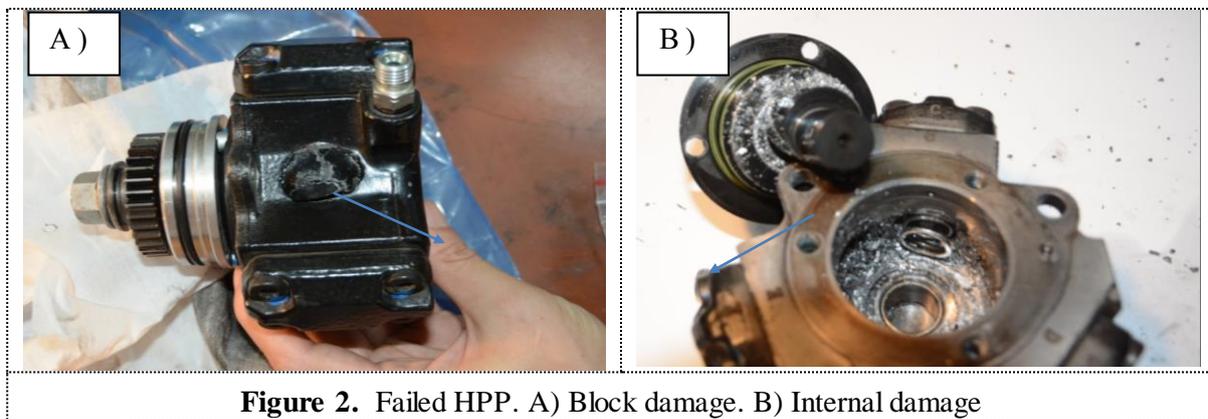


Figure 2. Failed HPP. A) Block damage. B) Internal damage

2.2. Macroscopic structure

Plunger units (including plunger and cylinder) were cut along cross section, as shown in Figure 3. Side wall surfaces of cylinders have obvious blue color area, indicating high temperature process occurred in this area.

2.3. Microscopic structure

Microstructure of one cylinder was shown in Figure 4. Scratches and particles can be seen on the side wall surface. Using Scanning Electron Microscopy (SEM) to observe the scratches and particles' morphology, as shown in Figure 5. As the energy spectrum curve of the substrate material of cylinder shown in Figure 5, the main chemical elements were Cr 3.7(wt %), Mn 0.8 (wt %) and balanced by Fe. Surface layer of cylinder may treated by carburizing process.

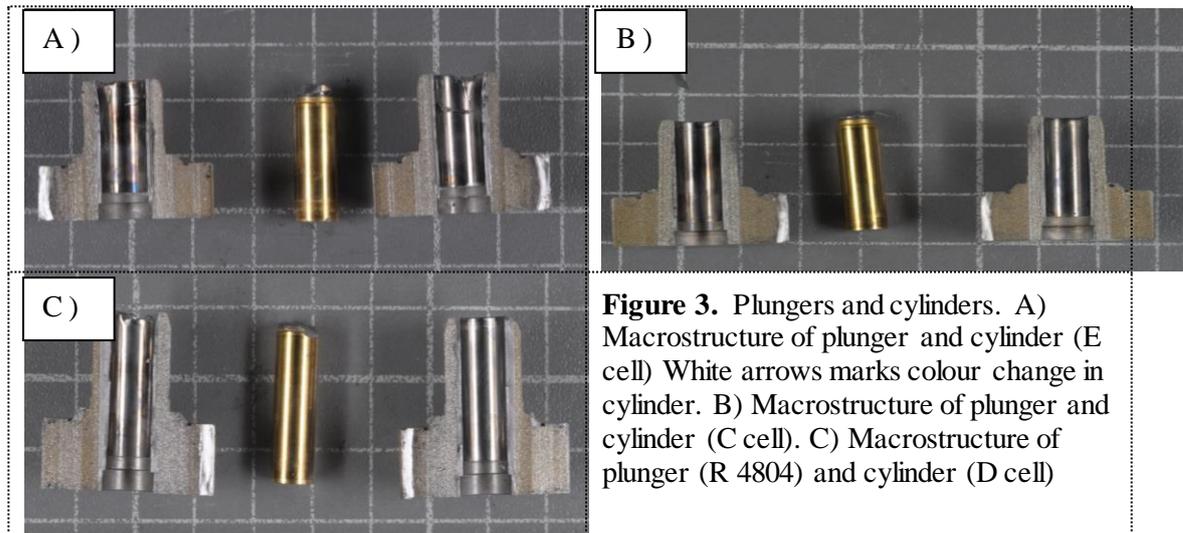


Figure 3. Plungers and cylinders. A) Macrostructure of plunger and cylinder (E cell) White arrows marks colour change in cylinder. B) Macrostructure of plunger and cylinder (C cell). C) Macrostructure of plunger (R 4804) and cylinder (D cell)



Figure 4. Surface macrostructure of cylinder

Particles on cylinder wall have two kinds of morphological characteristics, one was pits (fewer), energy spectrum analysis shows that the center of the pits include elements Al, Si and K. Another was particles, most of particles with chemical elements close to substrate material of cylinder, while few particles with chemical elements Al, Si and Ca. The micro topography of plunger was investigated too. The energy spectrum analysis shown that the main chemical composition of the plunger surface are Ti and N, which means Ti-N wear-resistant coating [5].

Due to internal components of failed pump were damaged seriously, some components can't be able to find. Abrasion, foreign particle or over heat may be related to this failure. So two more aged pumps are provided to do the contrastive analysis. One was from the same operation base Z and the other one was from base Y.

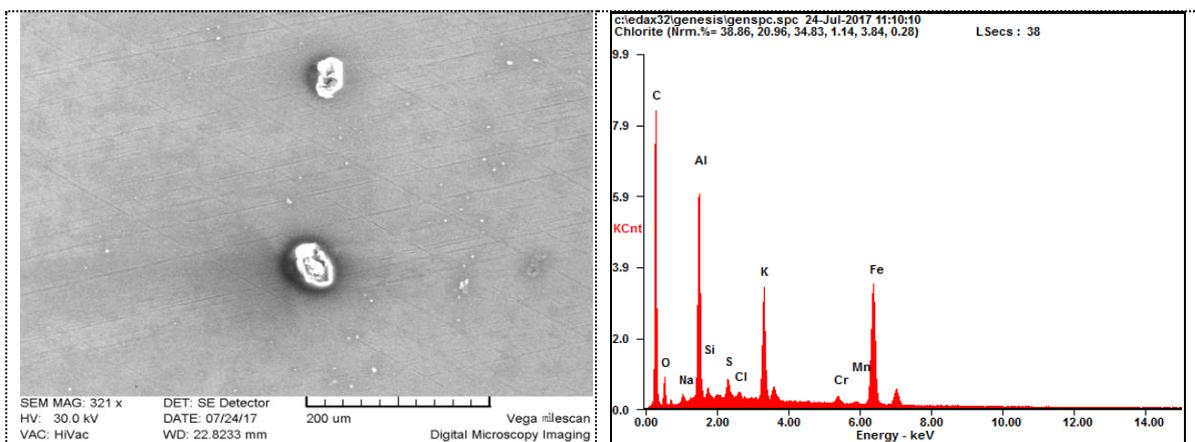


Figure 5. Surface microstructure of cylinder and energy spectrum of some particles

2.4. Material comparison

The high pressure fuel pump was imported from a foreign enterprise. The material standard is unknowing. In this work, plunger and cylinder were cut for metallographic analysis, for both Aged Pump Z and Failed Pump.

As shown in Figure 6, metallographic microstructures of plunger of Aged Pump Z and Failed Pump were the same with fine ferrite and cementite grain, the microstructure is very uniform and fine. Distribution of cementite was along ferrite grain boundary location with scale of 2 ~ 5 microns. Metallographic organization of cylinder wall was shown Figure 6, the surface layer was carburized. The thickness of carburized layer is uniform, the white stripe within the carburizing layer is decarbonization organization. Existing research show that the white decarbonization organization can gradually formation and evolution, with the extension of service life or load cycle. Its morphology has nothing to do with the treating process but with the service life and load cycle. Part of the surface appears light white, high temperature decarburization organization, which was caused by poor lubrication condition. Matrix organization are composed by martensitic, residual austenite and a small amount of cementite. Metallographic figure's difference in brightness mainly caused by corrosion, which has nothing to do with the material composition. So for material's microstructure, there are not deviations for failed pump and aged pump Z.

2.5. Abrasion comparison

Obvious impact marks or even falling coating, were found on the surface of rotor in Aged Pump Z, but were not found in Aged Pump Y, as shown in Figure 8. Blue color, over heat aero, can be found on the surface of plunger and cylinders in both failed pump and two aged pumps. Metallographic results show that these color change areas corresponding to the carburized layer suffering high temperature decarburization process in poor lubrication. The above results shown that the color change area related to the local high temperature. The color change area is associated with poor lubrication condition, but not the root cause for a stuck pump.

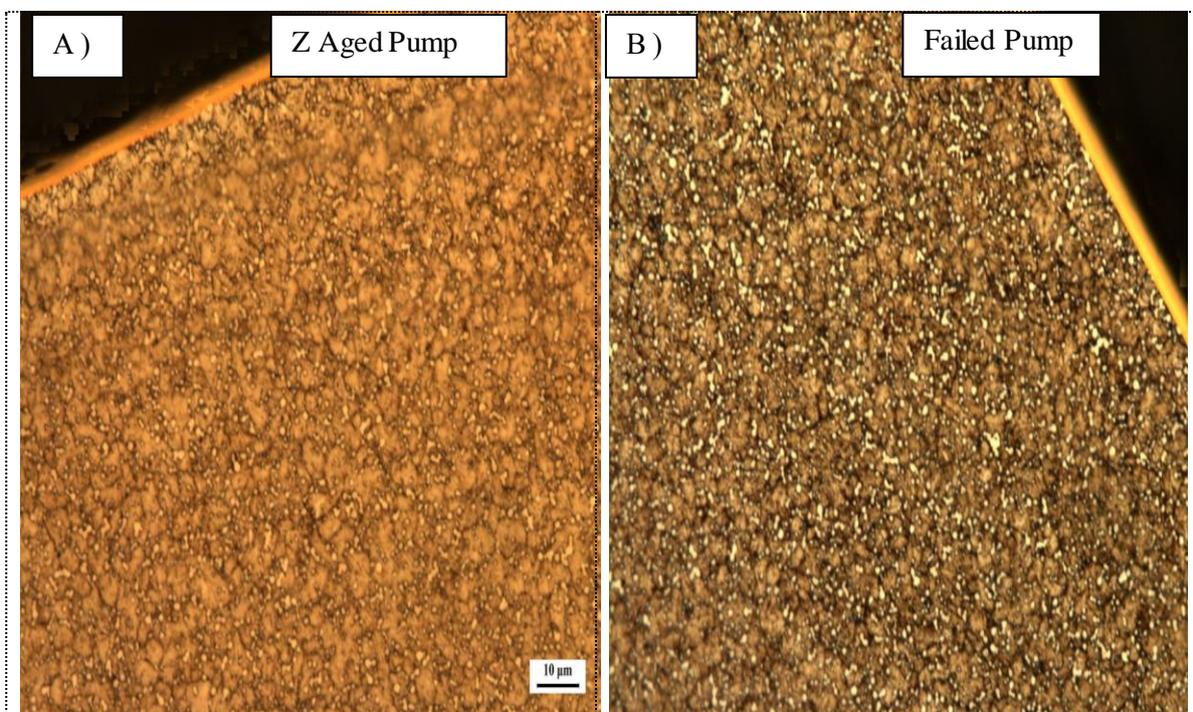
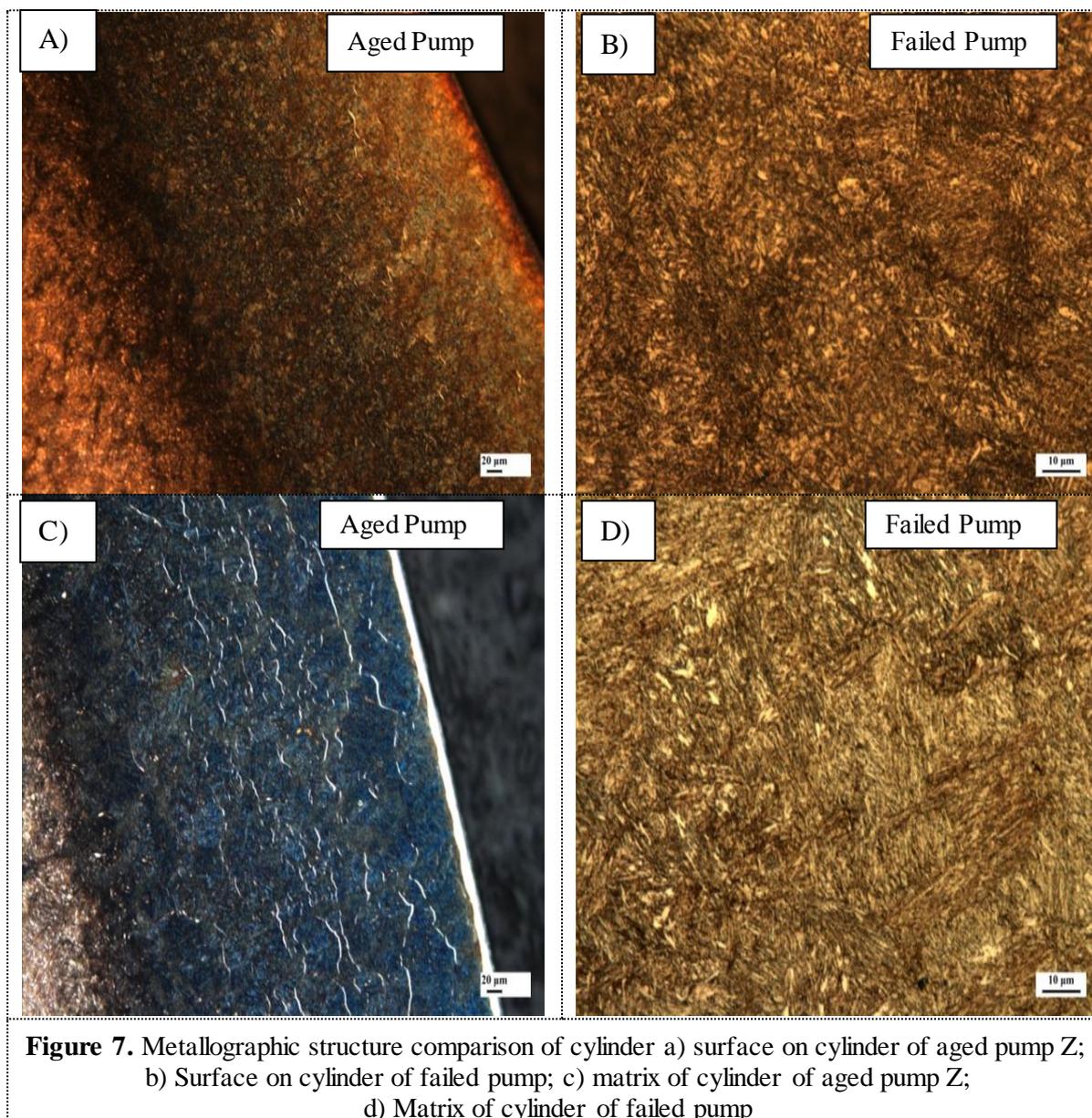


Figure 6. Metallographic structural comparison of plunger for HPP between Aged Pump Z and failed pump



Compare the traces of wear on the cylinder surface of failed pump and aged pumps as shown in Figure 9. Aged pump had circumferential distribution scratches, but the cylinder surface of failed pump contains a large number of axial distribution scratches. Circumferential scratches may be caused by the plunger's rotation. Axial and deflection axial scratches may be caused by particles blocking the plunger's movement. And some particles may break apart by the rotation of the plunger.

Put Aged Pump Z cylinder under the scanning electron microscope (SEM). Microstructure was shown in Figure 10. Most of the scratches were in parallel, with 0.4 microns width. But some significant axial directional scratches were found on the surface of cylinder, and the width and depth of scratches were more than one micron. According to the original pump design, the clearance between cylinder and the plunger is one micron. That indicated larger particles may cause the partial stuck, but under the rotation impact, plunger was pushed away from the stuck location, particles rolled across the wall of cylinder, left the similar scratches.

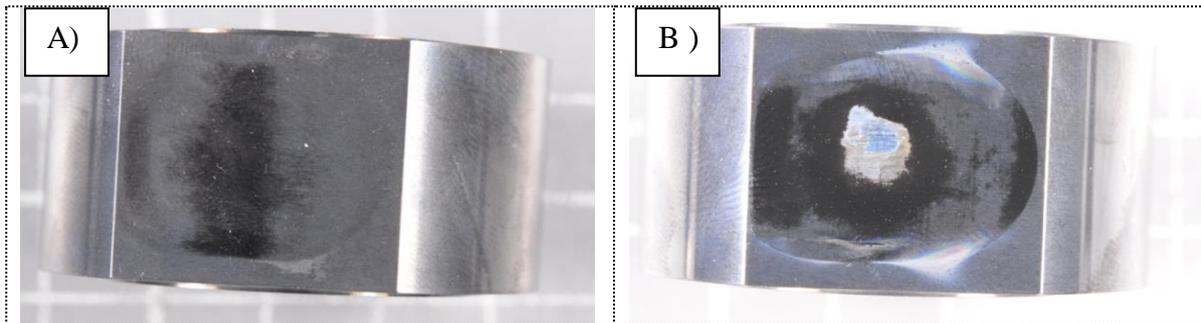


Figure 8. Rotor of camshaft of Aged Pump Y (a) and Aged Pump Z (b)

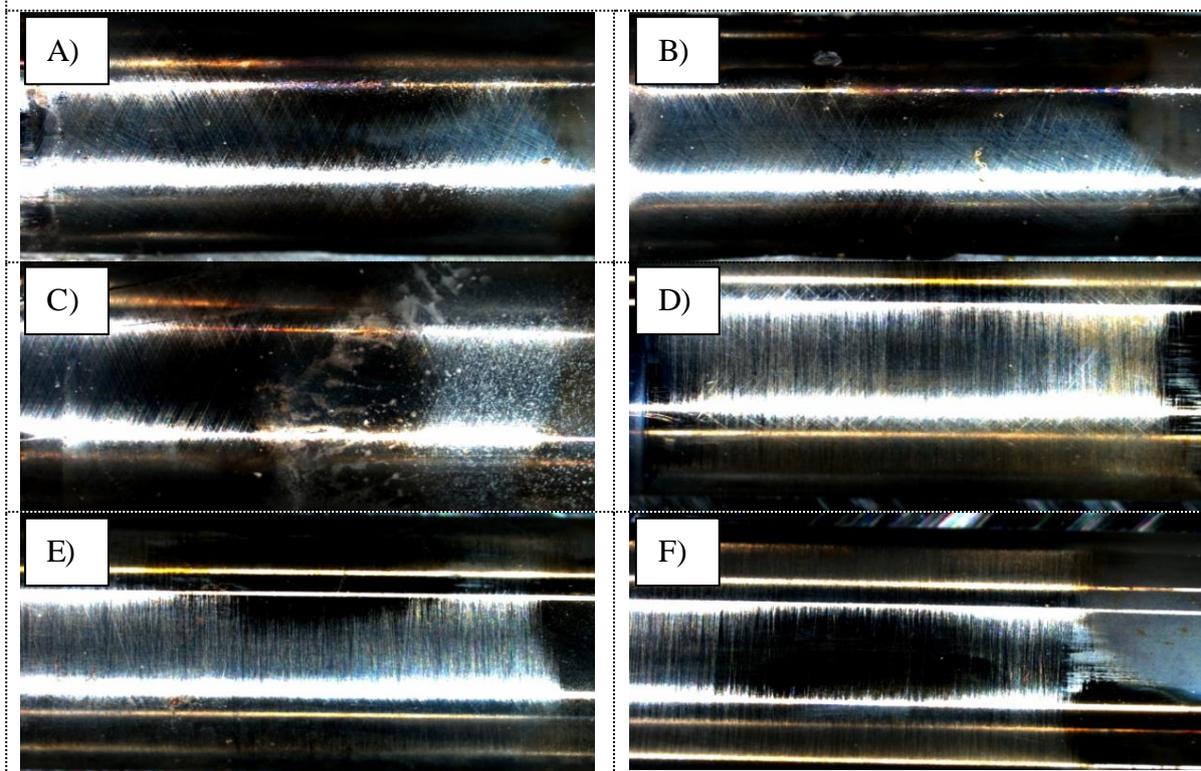


Figure 9. Comparison of wear track for Aged Pump Z and failed pump

2.6. Discussion

The analysis results shown that stuck plunger is the start cause of the HPP failure. The spring cannot press the plunger to the rotor. The rotor (Polygon) stroke the plunger and cut the plate off. The plate and the fragment of plunger were squeezed by rotor, and impacted against the pump's block.

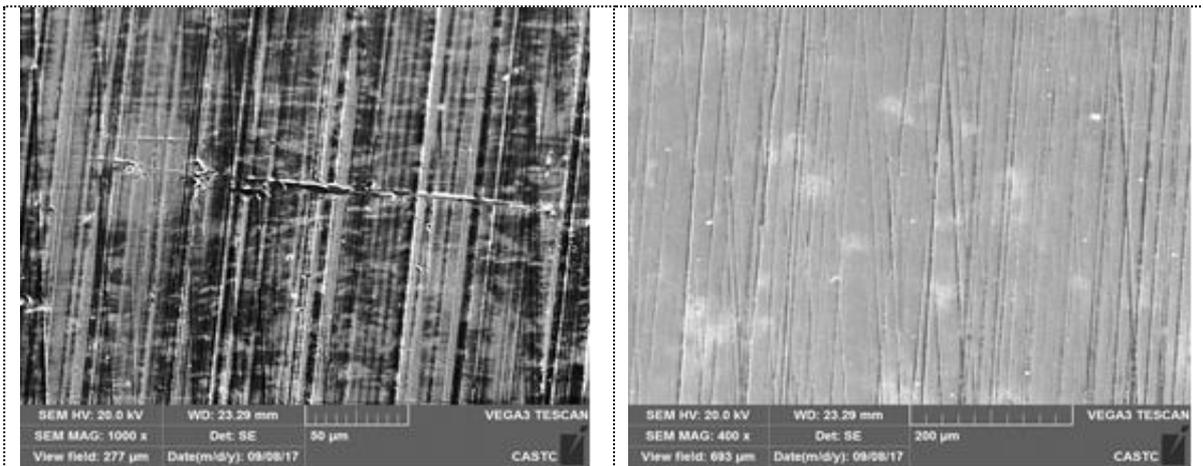


Figure 10. Scratches tracks along axial direction and scratches tracks along circumferential direction on aged pump Z

Currently, abnormal color were found on the inter surface of all three pumps. Color abnormal areas were smooth, with a small amount of scratches. Abnormal color caused by insufficient lubrication. No axial scratches on Aged Pump Y, indicated that stuck didn't happen. Obvious impact and friction axial scratches in aged pump Z indicated that plunger's rotation and reciprocating movement saving the plunger from stuck.

For microscopic observation, all the pumps appeared circumferential scratches on the surface of cylinder. This kind of scratches may cause by rotate and movement process of plunger. So those scratches may not cause a stuck pump. Aged pump Z had axial scratches, failed pump also had serious scratches on the surface of cylinder. [6-7].

The designed tolerance between plunger and cylinder is about 1 micrometer. So the 1 micrometer particles in the clearance between plunger and cylinder, can block the reciprocating movement of plunger. Some big particles found in the cylinder contains chemical element of Al, Si and O. This kind of particles were very common in the field, especially in desert area. But it is so common, the real source of the particles are difficult to verify.

3. Conclusions

The failure of a HPP cut the fuel off and forced the engine to stop. To investigate the root causes of HPP, two more fuel pumps (TSN 600h) with the same model number as the failed pump was received. After the investigation and analysis, conclusions are as followings:

- a. One plunger stuck because of foreign particles, the plunger was broken with sheared fracture feature, during the continuous rotation of the rotor. Subsequent fragments leading to the other two plungers' broken during the continuous rotation. Some of the larger fragments impacted against the pump block, causing the damage of the pump block.
- b. Three fuel pumps were received for analysis. All the surface of cylinders have abnormal color change, indicating poor lubrication happens frequently during working circles.
- c. Obviously axial scratches in failed pump and Aged Pump Z indicates that pumps are more sensitive to the foreign particles in base Z. The particles contains Al and Si oxide, but the real source is undetermined.

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