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Failure Analysis of High-Pressure Fuel Pumps Operated with Two Jet Fuels

by Nikhil Murthy, Caleb Matzke, Caleb McCoy, and Stephen Berkebile

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Failure Analysis of High-Pressure Fuel Pumps Operated with Two Jet Fuels

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14. ABSTRACT High-pressure fuel pumps (HPFPs) are an integral component in modern diesel engine systems. The durability of the HPFPs is highly dependent on the lubricity of the fuel being used. We examined five HPFPs operated with two jet fuels to determine the effect of fuel on component wear. Each subcomponent was analyzed for the type, location, topography, and composition of the worn surfaces. Pumps operated with fuel 1 exhibited a discoloration due to the formation of a thin surface film. Pumps operated with fuel 2 had several abrasive scratches and scuffing, which resulted in failure of the component.					
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1. Introduction

Small diesel internal combustion engines often rely on a high-pressure common rail system to deliver and inject fuel into the engine cylinders for combustion. These high-pressure common rail systems use high-pressure fuel pumps (HPFPs) to pressurize the fuel up to 200 MPa (29,000 psi) and supply it to the common rail.¹ Most diesel engine HPFPs are rotary plunger pumps that rely on the fuel to provide lubrication to the sliding components. This reliance on fuel for lubrication makes the durability of sliding components in an HPFP sensitive to the lubricating properties of the fuels. Those sliding components are at risk of long-term wear and sudden damage since fuels tend to have lower lubricity than traditional lubricants, and wear due to low-lubricity fuels has been well documented.² For example, a relatively low viscosity 0W-20 engine oil has a kinematic viscosity of approximately 45 cSt at 40 °C while viscosity for diesel fuel is 2.5–3 cSt at 40 °C.³ The lubricity drops further for U.S. Army vehicles that operate on jet fuel, which generally has a viscosity of 1.2–2 cSt at 40 °C.⁴

Since the operation of HPFPs is so dependent on the lubricity of the fuel, multiple approaches have been implemented to understand the relationship between fuel lubricity and HPFP durability. One approach is performing tribological evaluations of fuels on material coupons with a simplified contact geometry. This approach has the advantage of being quick, cheap, and easy to implement as a standard. Two methods using this approach have become standards for evaluating fuel lubricity: the ball-on-cylinder lubricity evaluator (BOCLE) test outlined in ASTM D5001 for jet fuels and the high-frequency reciprocating rig (HFRR) test outlined in ASTM D6079 for diesel fuels.^{5,6} Although these standard methods show meaningful differences in fuel lubricity, they are not always predictive of fuel pump performance, especially for low-lubricity fuels. Therefore, the development of better lubricity evaluation methods is still sought out, such as the high-frequency reciprocating rig–line contact test.⁷ Additionally, the standard fuel lubricity tests currently do not investigate scuffing failure, which is a present wear mode in HPFPs. Most methods for evaluating the “scuffing performance” slowly increase the applied load until a large increase in friction is observed.^{8,9} The ASTM D6078 scuffing load BOCLE (SLBOCLE) test was an initial attempt at creating a standard method of looking at scuffing behavior in fuel-lubricated systems, but the standard was withdrawn in 2021.¹⁰ One of the main problems with evaluating fuel lubricity via these types of coupon-level testing is that the procedures do not correlate strongly with each other.¹¹

Another approach to understanding HPFP operation is to model the system. Some examples are models by Koukouvini et al.¹² to model the cavitation within the

pump and Giuffrida et al.¹³ to model pressure and flow fluctuations within the pump. Protsenko et al.¹⁴ developed a simple kinematic model of a marine diesel fuel pump to propose improvements to their design. This modeling approach has the advantage of capturing complex behavior within the component without costly and time-consuming testing. Modeling can work well with coupon evaluation methods by acting as a bridge between the simplified systems and complex components. However, models tend to only look at one or two aspects of the system and, without proper verification, these models cannot be relied upon to capture contributions to HPFP performance.

A third approach to understanding HPFP operation is performing failure analysis of HPFPs previously used on vehicles. For example, Jiang et al.¹⁵ sought to determine the root cause of failure for HPFPs in piston aircraft engines. Deulgaonkar et al.¹⁶ looked at 79 HPFPs used in transport utility vehicles to determine the probability of subcomponent failure. Protsenko et al.¹⁴ observed failure of bushings in a marine diesel fuel pump. The major advantage of this approach is that the performance of these pumps is the closest to the intended operation. Also, little cost is associated with this method since it takes advantage of a used fuel pump discarded from a vehicle. The disadvantages of this approach are that the pumps often have a complex and mixed operation history, and the analysis is often employed after a problem is detected, which reduces the predictive value of these methods and the opportunity to detect the initial stages of damage.

The last approach, and the one used in this report, is operating an HPFP on a laboratory test stand. These laboratory test stands generally operate by using an electric motor to turn the HPFP and common rail and a set of injectors to aid in pressure and fuel flow control. Operation on a test stand has the advantage of capturing the full complexity of the component while providing the experimenter control over the HPFP operating conditions. The main disadvantages of this approach are that tests are more expensive and time-consuming than the other methods. Wei et al.¹ have used a fuel pump test stand to monitor the pressure fluctuation during the pumping cycle. Petrea et al.¹⁷ have examined the contributions to the total noise generation from the various subcomponents. An HPFP test stand at Southwest Research Institute was built to operate at a wide range of operating conditions¹⁸ and has been utilized in multiple experiments, such as the testing of lubricity doser filters to improve HPFP durability¹⁹ and evaluating new HPFP designs.²⁰ Labeckas et al.²¹ have used a similar test stand to show that fuel pumps using ethanol–diesel blends have reduced output due to decreased lubricity of the fuel.

The HPFP model analyzed in this study is the Bosch CP3, which has become an industry benchmark since its introduction in 2001.²² A CP3 HPFP works to

pressurize fuel by compressing it with a set of three plungers driven by an eccentric cam shaft. Figure 1 shows a simple representation of a typical CP3 pump. The fuel first enters through an electronic metering valve, which aids in controlling the pressure of the high-pressure rail by controlling the flow of fuel drawn into the HPFP. This valve never fully closes due to the orifice design.²³ The fuel is then drawn through several low-pressure channels towards the plungers. Each plunger sits within a cylindrical chamber within the steel housing. The plungers move in and out of the cylindrical chamber with two strokes, the compression stroke and intake stroke. The plunger remains about 12.5 mm within the cylindrical chamber to maintain the seal. During the intake, the inlet valve opens to allow the low-pressure fuel to enter the chamber, and the outlet check valve remains closed to prevent backflow from the high-pressure rail. The valves change position during the compression stroke to allow the newly pressurized fuel to exit out towards the high-pressure rail. The clearance between the plunger and housing is extremely small (2–4 μm) to form a tight seal for the high-pressure fuel.^{2,23} The camshaft is typically driven by the engine at half the engine rotation speed. The rotating shaft causes the cam ring to translate in a circular pattern due to the eccentricity of the shaft. The cam ring contacts a bucket tappet that in turn contacts the plunger, providing the force to push the plunger away from the camshaft during the compression stroke. A return spring moves the plunger back towards the cam ring during the intake stroke. The main contact surfaces in the HPFP are between the camshaft/cam ring, cam ring/bucket, bucket/plunger, plunger/housing, inlet-valve/valve-seat, check-valve/housing, and at shaft bushings. The contact pairs and type of motion differ slightly between different HPFP models, but the primary mechanism of pumping remains compression in a cylinder with a cam system for the Bosch CP3 and most other rotary plunger HPFPs.

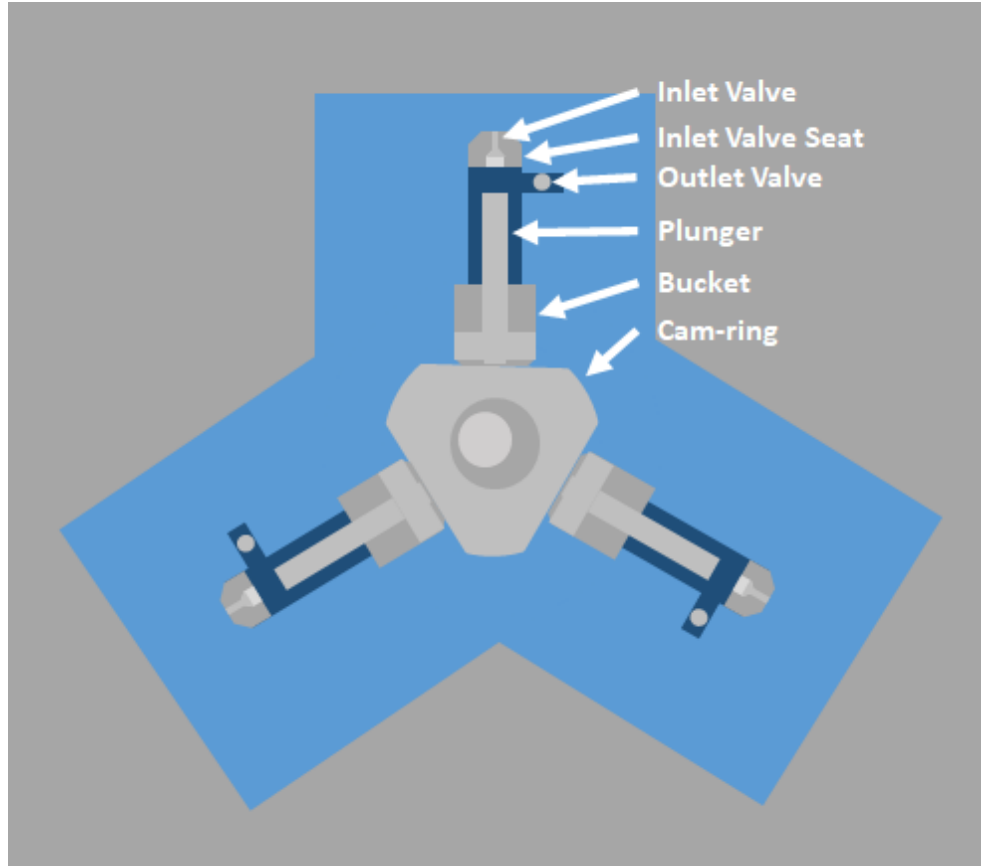


Figure 1. Bosch CP3 fuel HPFP.

In this study, we characterized the material damage on the subcomponents of Bosch CP3 HPFPs that have been operated with jet fuel on laboratory HPFP test stands. By understanding the location and type of wear present within this pump, we gain insight into how the entire class of rotatory plunger HPFPs behave when operating with low-viscosity fuel, such as jet fuel.

2. Procedure

The HPFPs used in this study were four Bosch CP3 pumps with service No. 0445010264. The service number is a unique identifier for each submodel of the pump, as several submodels exist with variations such as the location of external fittings, flow rate capacity, surface coatings, and the option of an integrated low-pressure gear pump. Table 1 summarizes the condition of each pump after testing. Pump 1 was pristine. All other pumps were operated with heavy fuels (e.g., jet fuels JP-8 and F-24) that were compliant with the jet fuel specifications MIL-DTL-83133H²⁷ and ASTM-D1655.²⁸ However, the HPFPs were designed to operate on diesel fuel, which has different properties than the jet fuel used in this study (e.g., lower lubricity and sulfur content). Two batches of fuel were supplied are

subsequently referred to as fuel 1 and fuel 2, with their properties shown in Table 2. Pump 2 was operated on a test stand at Pike Peaks Test Labs for 1052 h with fuel 1 before a decrease in flow occurred. It was concluded in a separate report that this was due to clogging of the electronic metering valve with polymer contaminant from the fuel lines.²⁴ It is assumed that pump 2 did not experience significant damage due to the contamination and that its state after testing was similar to that of a used, but not failed, HPFP. Pump 3 was also operated at Pikes Peak Test Labs with fuel 1 but continued for 1800 h without a drop in operating pressure. Pumps 4 and 5 were operated at a test stand at Exergy Engineering with fuel 2 for 476 h and 1200 h, respectively, before a decrease in flow rate by 18%–41% and an increase in noise due to seizure of one of the plungers.

Table 1. HPFP operating history and condition.

Specimen No.	Experiment duration (h)	Location of experiment	Fuel	Final condition
Pump 1	0	NA	NA	Pristine
Pump 2	1052	Pikes Peak Test Labs	Fuel 1	Used
Pump 3	1800	Pikes Peak Test Labs	Fuel 1	Used
Pump 4	476	Exergy Engineering	Fuel 2	Failed
Pump 5	1200	Exergy Engineering	Fuel 2	Failed

Table 2. Fuel viscosity and lubricity.

Fuel name	Fuel category	Viscosity at 40 °C (cSt)	BOCLE⁵ wear scar diameter (μm)	HFRR⁶ wear scar diameter (μm)
DF-2	Diesel	2.52	464 ± 30	404 ± 58
F-24	Jet fuel	1.3	545 ± 12	575 ± 12
Fuel 1	Jet fuel	1.13	588 ± 19	650 ± 44
Fuel 2	Jet fuel	1.34	589 ± 31	555 ± 11

The pumps were disassembled and inspected visually. The subcomponents from the plunger–bore assembly with the most damage were chosen for further investigation. Photographs were taken of the various parts using a Canon DS126311 camera. Bright-field optical micrographs were taken using a Zeiss LS700 microscope. 3D surface topography maps of various surfaces were taken using a Zygo ZeGage scanning light interferometer. The surface roughness was calculated according to ISO 25178 by taking the average and standard deviation of five reduced-area maps to provide a measure of the local surface variations and roughness. Micrographs were taken of the surface using a Hitachi SU3500 scanning electron microscope (SEM) and the surface composition was determined using a Bruker XFlash 630M energy dispersive spectrometer (EDS) with a 20 kV

accelerating voltage. Raman spectroscopy was conducted using a Horiba LabRAM Raman microscope with a laser wavelength of 532 nm. The material hardness was measured with the Rockwell hardness scale (HRC) for pump 1 subcomponents when possible.

3. Results and Discussion

3.1 Camshaft and Cam Ring

3.1.1 Pump 1 (0 h, Pristine)

The contacting surfaces in this Bosch CP3 HPFP with service No. 0445010264 were mostly uncoated steel except for the surface of the cam ring, which contained a shiny black coating. Photographs of the camshaft with the cam ring of this pristine pump 1 are shown in Figure 2. The black coating on the surface of the cam ring contrasted clearly with the uncoated steel shaft. The cam ring contained a surface grind oriented parallel to the shaft and perpendicular to the direction of sliding with the bucket. The shaft contained a circumferential grind parallel to the direction of rotation with the ring.

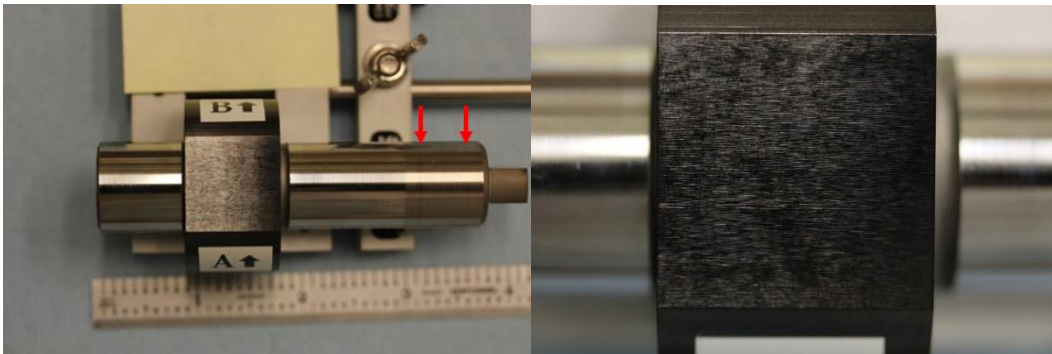


Figure 2. Camshaft and cam ring from pump 1 (0 h, pristine).

In Figure 3, an optical micrograph of the surface of the pump 1 cam ring is shown. The main features are the horizontally oriented grind marks. The number of grind marks present in the center of the cam ring was large because of the lack of run-in present in the pristine surface.

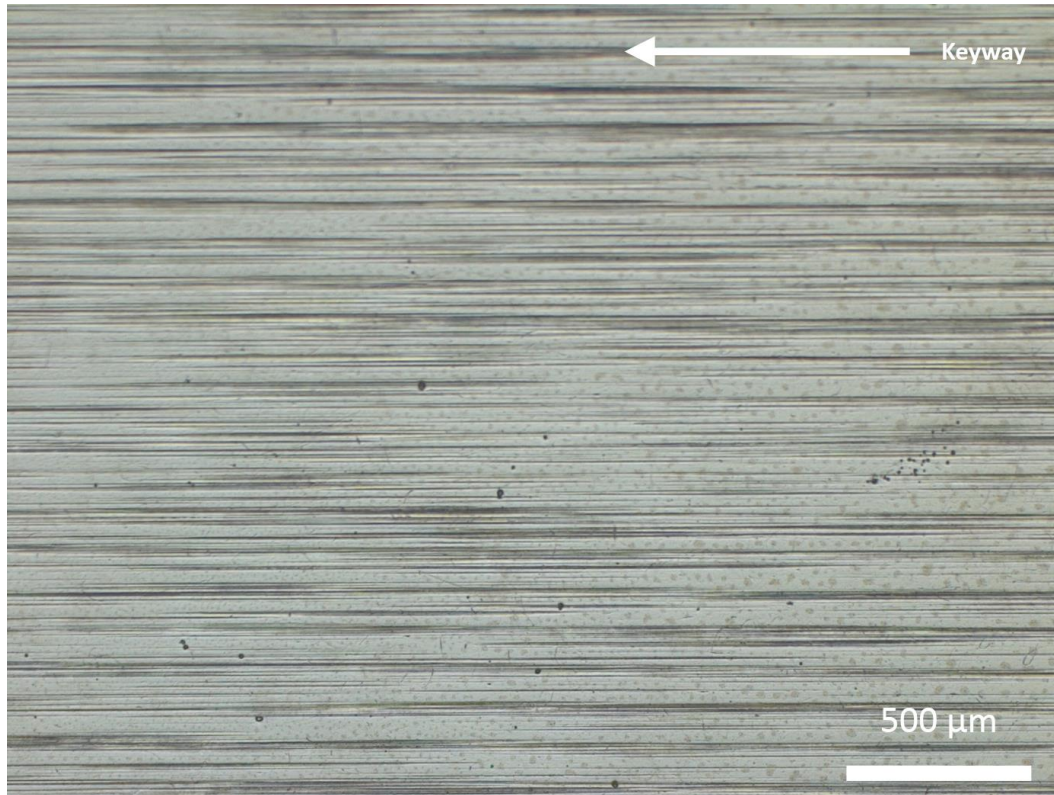


Figure 3. Bright-field optical micrograph of one of the flat faces of the cam ring from pump 1 (0 h, pristine).

A surface profile of one of the flat surfaces in the cam ring is shown in Figure 4. Each surface is approximately square with a length and width of 21 mm. There was a slight convex curvature across the circumferential direction with a height variation of 2 μm across the full length. The roughness of the cam-ring surface was $S_a = 61 \pm 12 \text{ nm}$.

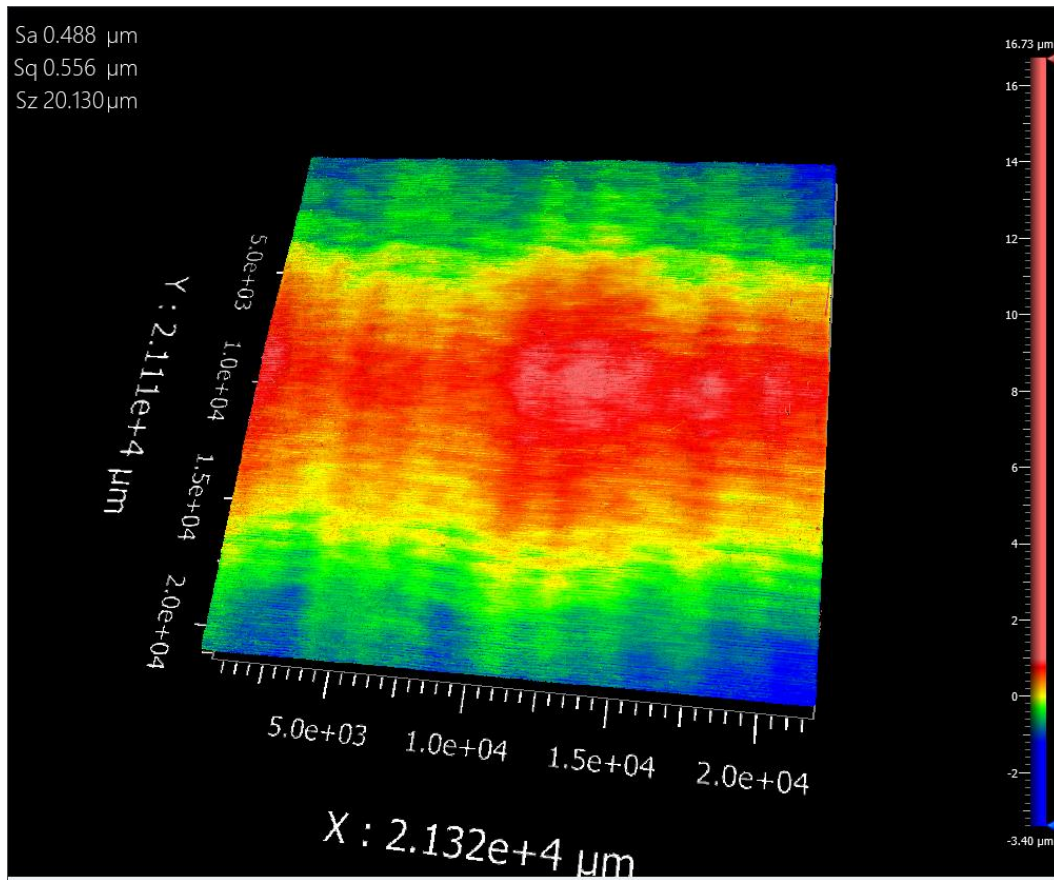


Figure 4. Surface profile of one of the flat faces of the cam ring from pump 1 (0 h, pristine).

Micrographs of the surface taken with the SEM secondary electron (SE) detector are shown in Figure 5. The coating appears smooth until observed at high magnification, where it can be seen from the micrograph on the right that fine ($<1 \mu\text{m}$) features exist.

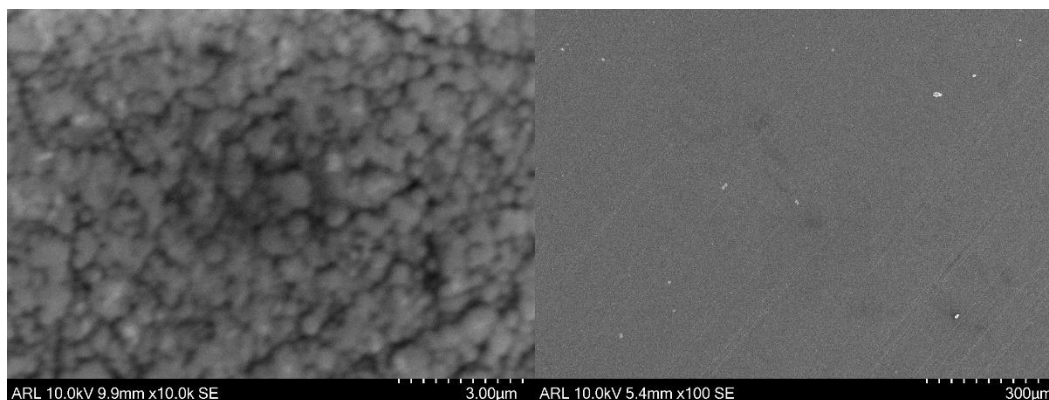


Figure 5. Secondary electron SEM micrographs of one of the flat faces of the cam ring from pump 1 (0 h, pristine).

The elemental composition of the coating was determined from the EDS spectra shown in Figure 6. Although measured with an electron beam energy of 20 keV, the figure only shows the spectrum between 0 and 10 keV where the majority of the peaks were present. The y-axis is shown on a square root scale to show the low energy peaks more clearly. The major elements are carbon and tungsten, with minor concentrations of chromium, silver, and iron. The structure of the coating is discussed in more detail in Section 3.1.3.

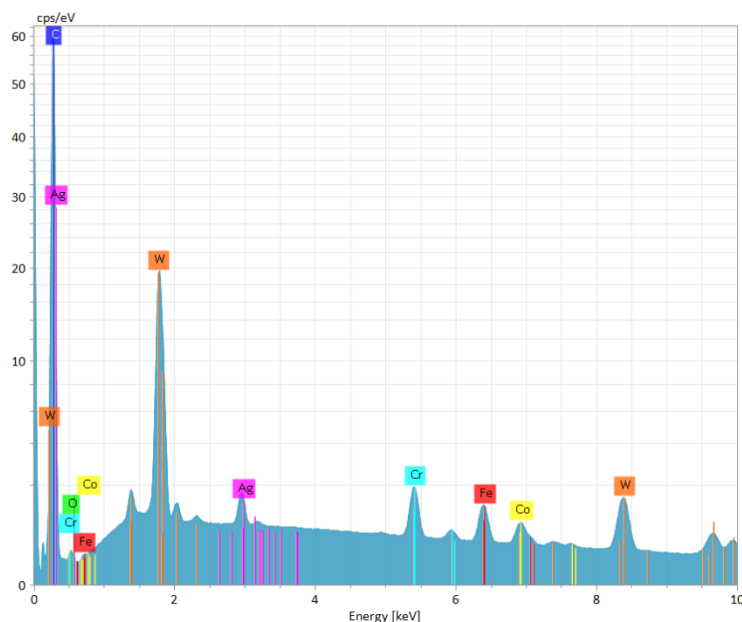


Figure 6. EDS spectra of one of the flat faces of the cam ring from pump 1 (0 h, pristine).

The chemical composition of the coating was determined using the Raman spectra shown in Figure 7. The spectra shows the most prominent peak at 1550 cm^{-1} with a small shoulder peak at 1300 cm^{-1} . These peaks correspond well with measurements of diamond-like carbon from literature.²⁵

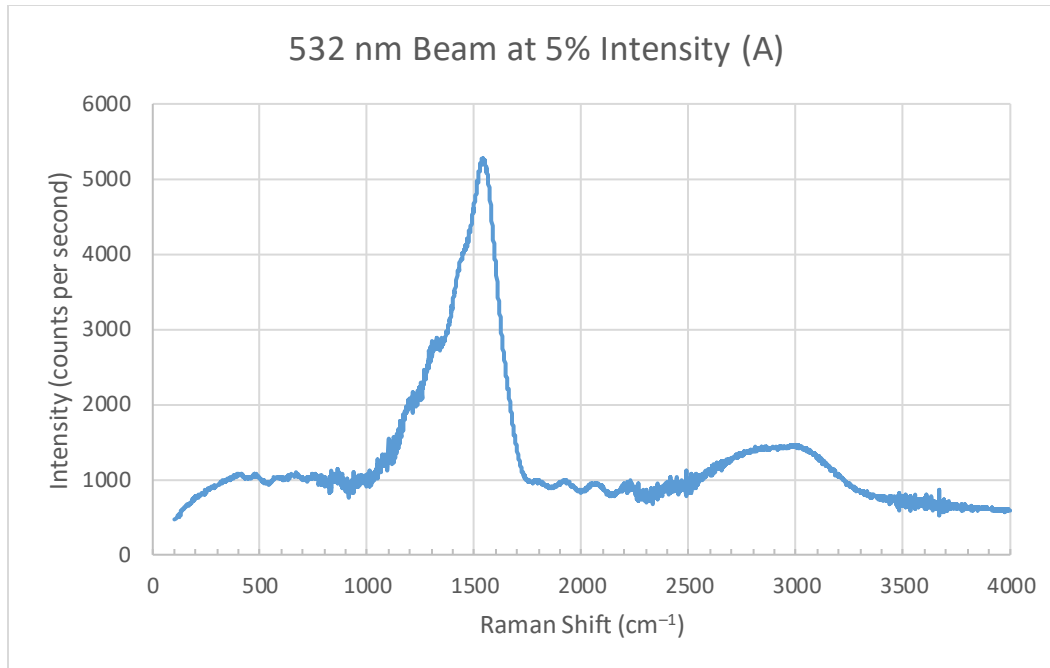


Figure 7. Ramanspectra of one of the flat faces of the cam ring from pump 1 (0 h, pristine).

The hardness of the cam ring was 61.2 ± 0.7 HRC and the hardness of the camshaft was 60.4 ± 1.1 HRC.

3.1.2 Pump 2 (1052 h, Used until Inlet Clogged)

Wear was observed on several surfaces of pump 2, which had 1052 h of use before shutdown due to a clogged inlet metering valve (Figure 8). This clogging was not due to damage of the fuel pump, but from degraded material from the test bench redepositing within the pump.²⁴ The shaft contained two circumferential wear marks highlighted by the red arrows towards the end with the drive key at the point where the shaft interfaces with a pair of seals in the housing. Each of the flat faces on the cam ring contained an oval-shaped wear mark, which is offset towards the side of the cam ring that contacts the bucket during the intake stroke. We will refer to this side of the cam ring as the “intake side” and the other side as the “compression side.”

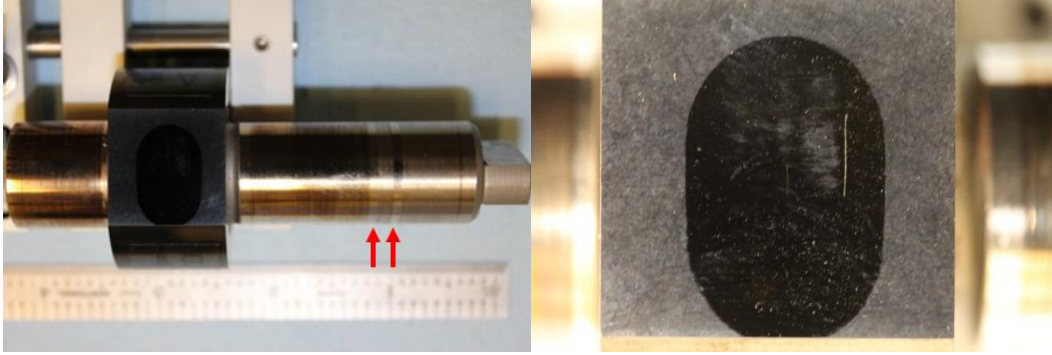


Figure 8. Camshaft and cam ring from pump 2 (fuel 1, 1052 h).

Bright-field micrographs of the cam-ring surface are shown in Figure 9. The micrograph shows a reduction of horizontally oriented grind marks compared with the pristine pump, which is likely due to the common phenomenon of surface roughness reduction upon sliding, referred to as “run-in.” Run-in is generally beneficial to a surface in reducing friction and wear. The coating was still intact.

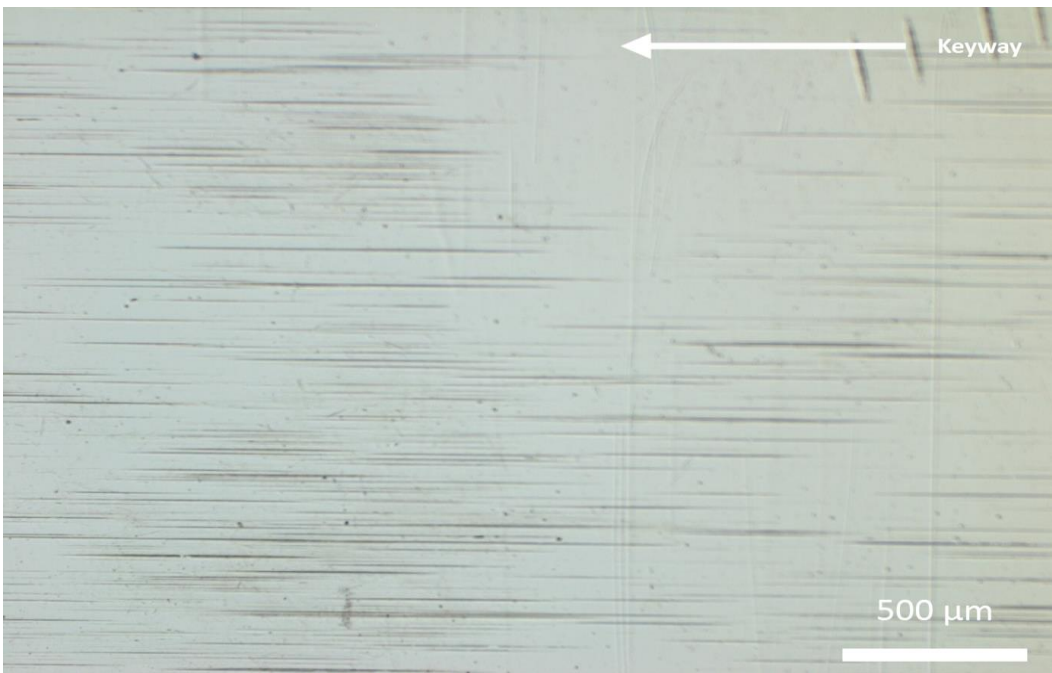


Figure 9. Bright-field optical micrographs of one of the flat faces of the cam ring from pump 2 (fuel 1, 1052 h).

The surface profile of the flat face shows that the surface maintained much of its original form with the addition of the oval-shaped wear mark described earlier (Figure 10). The wear mark was approximately 1 μm deep along edges; however, there was a circular region centered towards the intake side within the oval-shaped mark that experienced reduced wear. The low-wear region does not extend all the way to the edge of the wear mark. We suspect that this low-wear region is caused

by rocking motion of the bucket during the pumping cycle. It was observed that the axes of the pump bores are approximately 1.4 mm offset from the axis of the camshaft. This offset allows the cam ring to experience lower torques than it would without an offset, but it also means that the direction of the torque applied to the cam ring alternates. We suspect that the alternating torque causes a rocking motion of the cam ring causing the heaviest load to alternate between the two leading/following edges of the bucket during sliding. We can see evidence of this rocking motion by the reduced wear we observe from the circular region within the wear mark where the bucket would have shifted from one edge to the other. Lastly, increased wear was observed at the ends of the wear scar, which may have been caused by the low hydrodynamic fluid protection at the turnarounds where the entrainment speed approaches zero. The roughness of the cam-ring surface was $S_a = 49 \pm 24$ nm inside of the worn area. The decrease in roughness from the pristine surface was likely due to run-in.

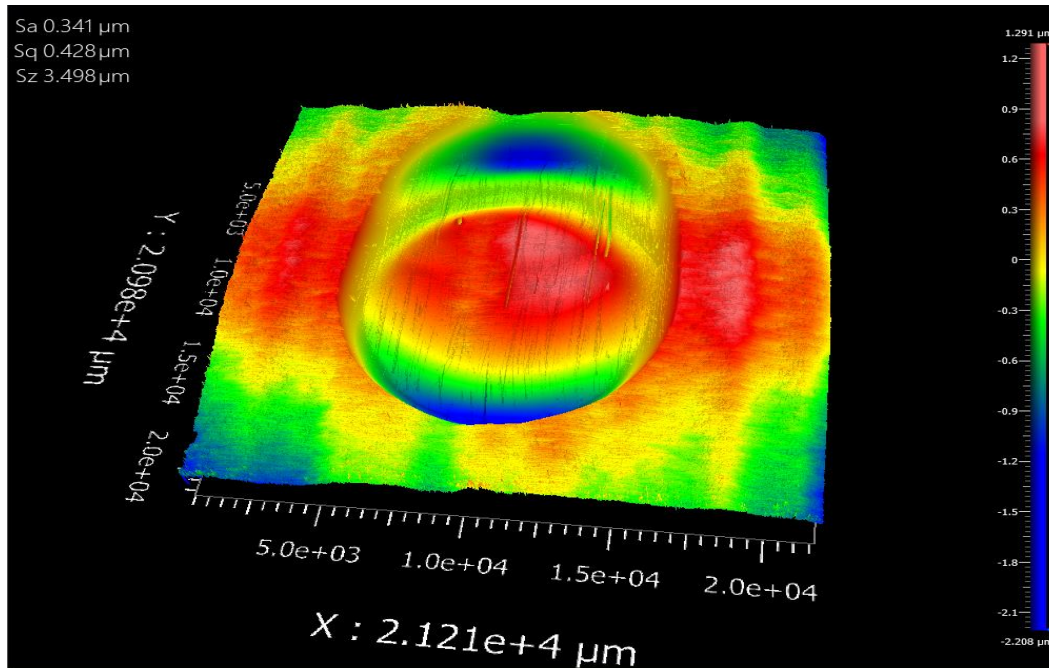


Figure 10. Surface profile of one of the flat faces of the cam ring from pump 2 (fuel 1, 1052 h).

3.1.3 Pump 3 (1800 h, Used until Inlet Clogged)

Pump 3 was operated without decrease in function for 1800 h. The camshaft and cam ring from pump 3 exhibited many of the same wear patterns as pump 2 but also showed signs of coating wear. As shown in Figure 11, the coating was worn away on the intake side of the wear mark, exposing the bare steel surface.

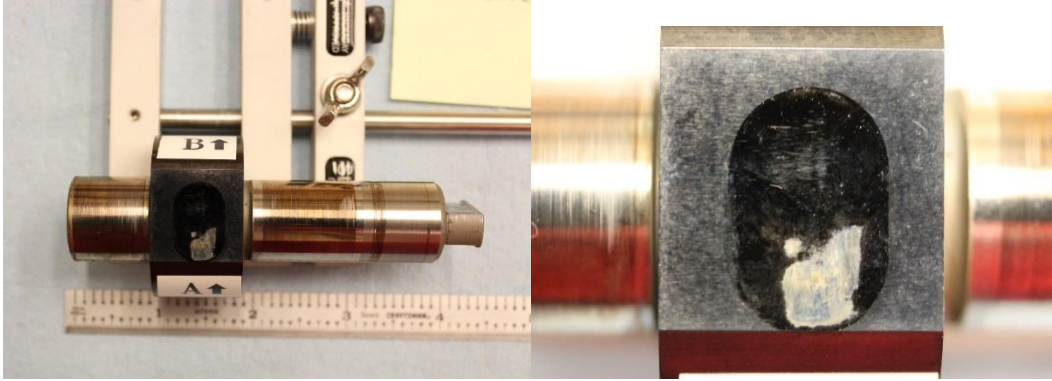


Figure 11. Camshaft and cam ring from pump 3 (fuel 1, 1800 h).

The wear of the coating can be seen in detail in the optical micrograph of the cam-ring surface shown in Figure 12. The upper left corner of the micrograph shows the coating, while the lower right corner has the exposed steel. There was a gradual transition between the two regions, suggesting that coating was worn away as opposed an abrupt transition resulting from chipping or delamination. There was evidence of substantially more abrasive wear and a dark-brown appearance where the coating was worn.

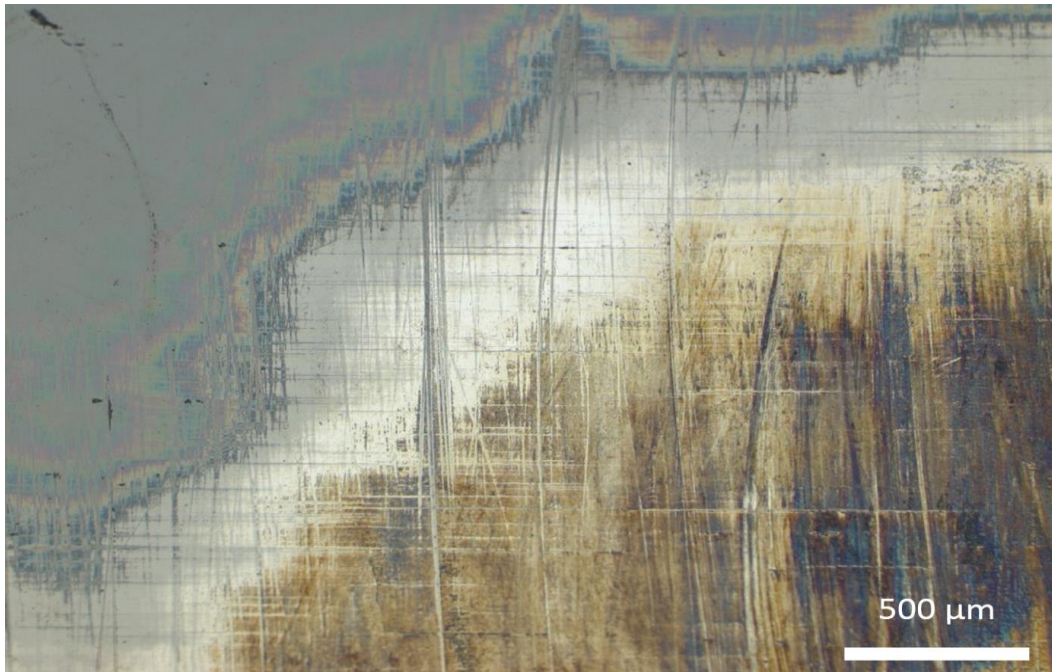


Figure 12. Bright-field optical micrograph of one of the flat faces of the cam ring from pump 3 (fuel 1, 1800 h).

The surface profile of the pump 3 cam ring (Figure 13) is similar to pump 2 in that it has the large oval shape with a central circular patch with less wear. The main difference is that pump 3 has a rougher surface near and around the area where the coating was worn. We can see a deeply worn area shown in blue in Figure 13 that matches the shape of the steel patch in Figure 11. The roughness of the cam-ring surface was $S_a = 56.2 \pm 43$ nm.

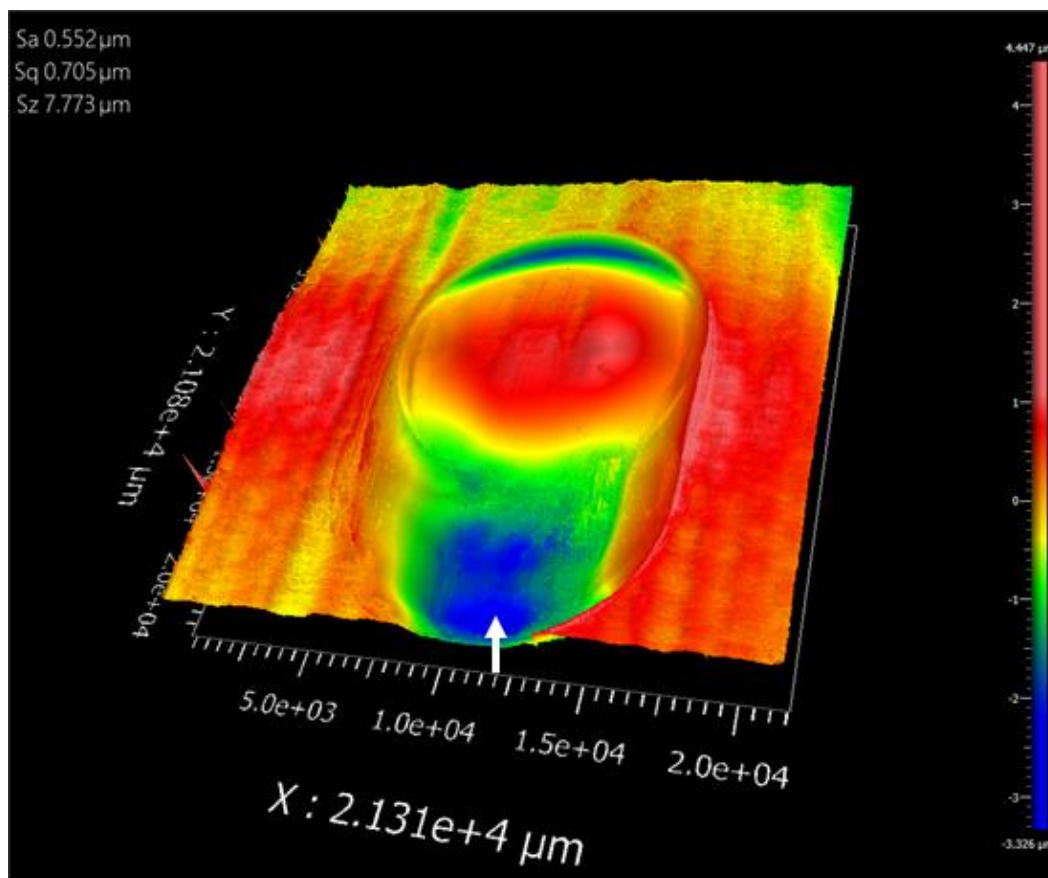


Figure 13. Surface profile of one of the flat faces of the cam ring from pump 3 (fuel 1, 1800 h).

The worn area of the pump 3 cam ring was observed with both SEM (Figure 14) revealing three layers material. The regions in the SEM micrograph—starting from top to bottom—are the main coating (grey), the coating bond layer (light grey) and the exposed steel (dark grey). The EDS spectra (Figure 15) shows that the major elements present in this micrograph are carbon, tungsten, iron, oxygen, and chromium. The steel was predominantly iron but also contained oxygen, suggesting oxidation of the steel. Chromium was also present in small amounts. Chromium is a common additive for low-alloy tool steel such as AISI 52100. Moving up into the bond layer, there was a large amount of tungsten but also a small increase in the chromium concentration. This may be due to chromium migrating to the surface during the coating process, but it is more likely due to chromium used as a bonding layer. Lastly, carbon was the main contributor to the main coating. Tungsten was also observed; however, because of the low surface sensitivity of EDS, it is not possible to tell whether this is from the main coating or the bond layer. Small amounts of silver were observed in the spectra, but the quantity was too low to determine the location. Since the silver was present in high quantities in the pristine pump (Figure 5) where the coating was thicker, it is hypothesized that the silver

may be an impurity or dopant present in the carbon layer. By combining this information with the previous Raman spectra (Figure 6), it can be concluded that the material on the cam ring is likely a diamond-like carbon coating containing tungsten on a chromium bond layer with possible tungsten content on a low-alloy chrome–steel substrate.

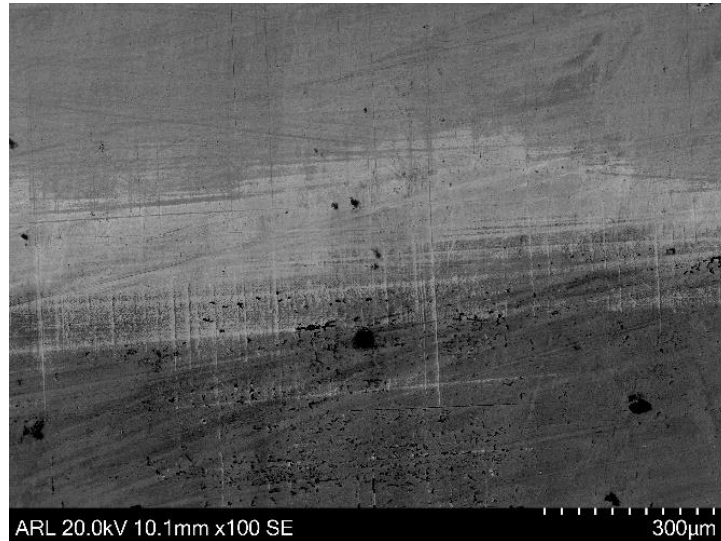


Figure 14. SEM micrograph taken with SE detector of the cam ring from pump 3 (fuel 1, 1800 h).

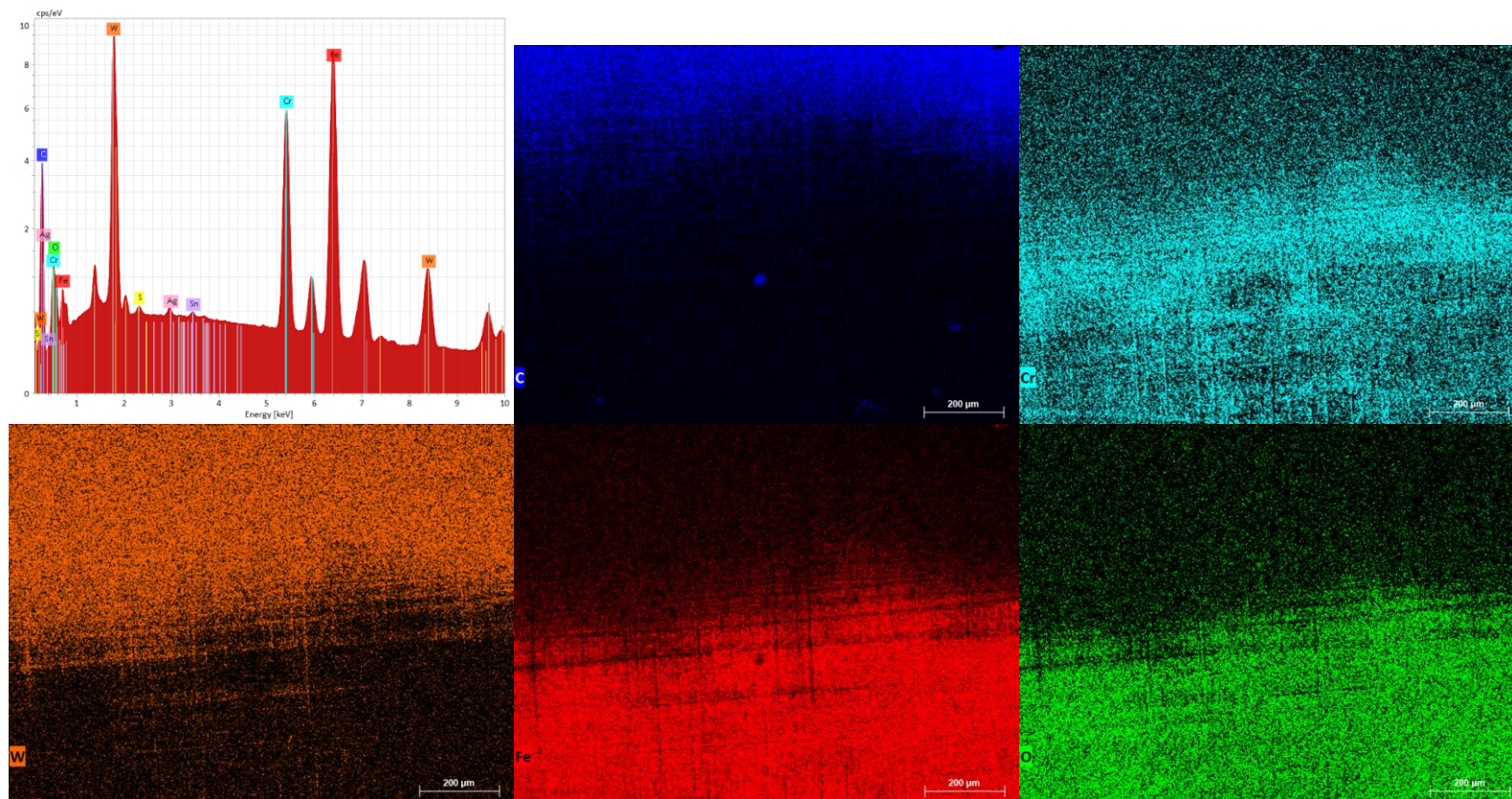


Figure 15. EDS elemental spectra (top left) and EDS elemental maps of carbon (top center), chromium (top right), tungsten (bottom left), iron (bottom center), and oxygen (bottom right) of the cam ring from pump 3 (fuel 1, 1800 h).

3.1.4 Pump 4 (476 h, Failure due to Plunger Seizure)

Pump 4 ran for 476 h before a decrease in flow occurred beyond the stop criterium due to seizure of a plunger in the cylinder. Compared with pumps 2 and 3, pump 4 appeared to have less wear of the coating on the cam ring (Figure 16). The oval-shaped wear scar was fainter and there was no exposed steel. Wear marks were still seen on the camshaft.

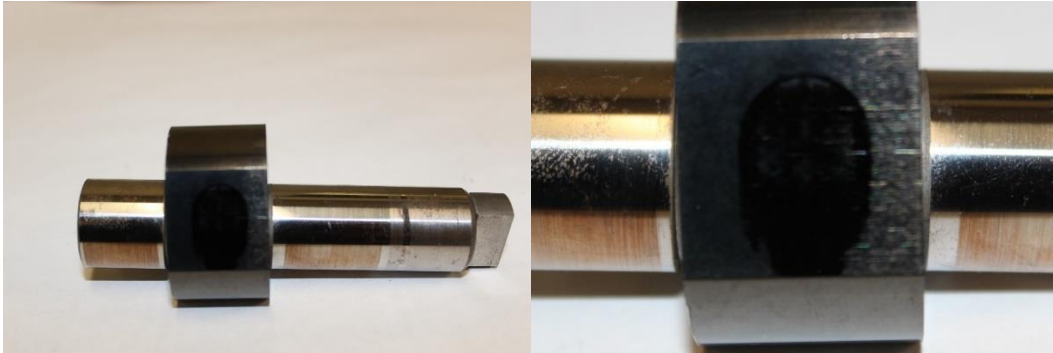


Figure 16. Camshaft and cam ring from pump 5 (fuel 2, 476 h).

The surface of the pump 4 cam ring within the region contacting the bucket is shown in more detail in Figure 17. The surface had a run-in appearance similar to pump 2 (Figure 8), but with more horizontal grind marks visible.

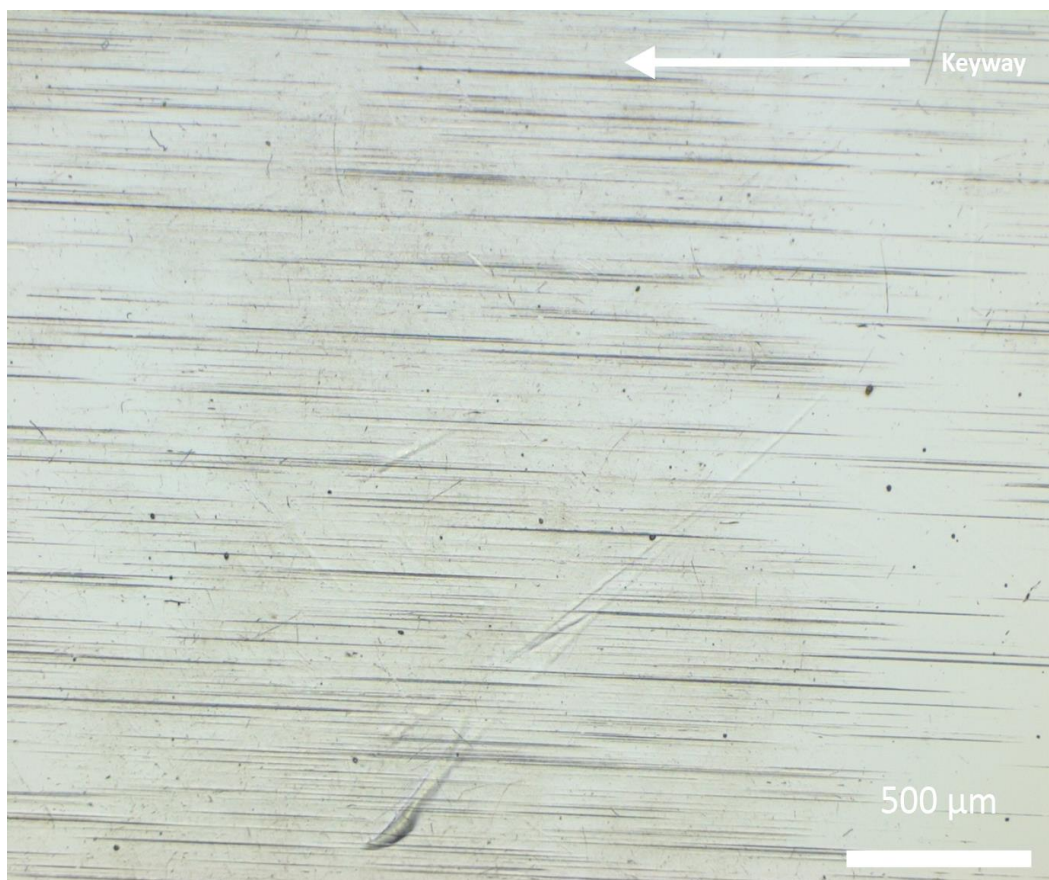


Figure 17. Bright-field optical micrograph of one of the flat faces of the cam ring from pump 4 (fuel 2, 476 h).

The surface profile of the pump 4 cam ring (Figure 18) had some wear on the region contacting the bucket similar to the wear pattern seen in pump 2. The difference in roughness was minor compared to the pristine pump. The roughness of the cam-ring surface was $S_a = 73 \pm 10$ nm.

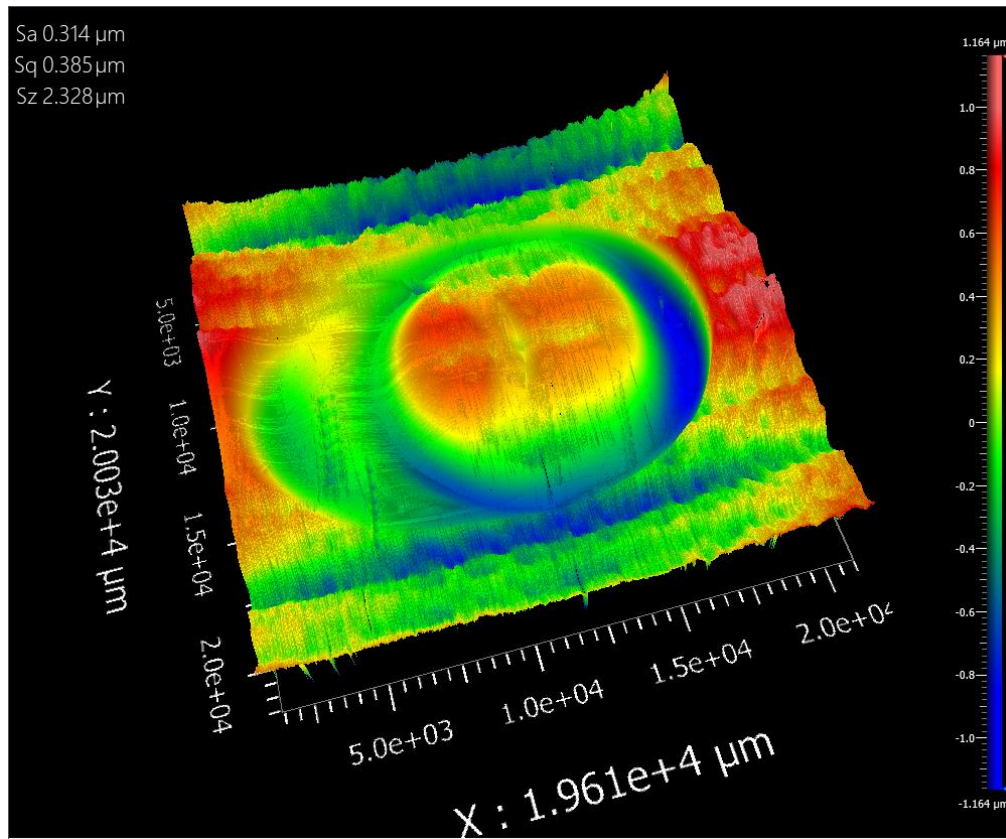


Figure 18. Surface profile of one of the flat faces of the cam ring from pump 4 (fuel 2, 476 h).

3.1.5 Pump 5 (1200 h, Failure due to Plunger Seizure)

Pump 5 ran for 1200 h before a decrease in flow occurred beyond the stop criterium due to seizure of a plunger in the cylinder. As seen in Figure 19, pump 5's camshaft had the two wear marks from the seals and the cam ring had the oval-shaped wear mark, similar to the other pumps. The appearance was similar to pump 4 where little wear was observed and the wear scar was faint.



Figure 19. Camshaft and cam ring from pump 5 (fuel 2, 1200 h).

Bright-field optical micrographs of the cam ring from pump 5 on the region contacting the bucket surface (Figure 20) showed many horizontal grind marks intact and very little run-in. Pump 5, which was operated with fuel 2, appeared to have less wear than pump 2 (Figure 9), which was operated with fuel 1 for a similar duration.

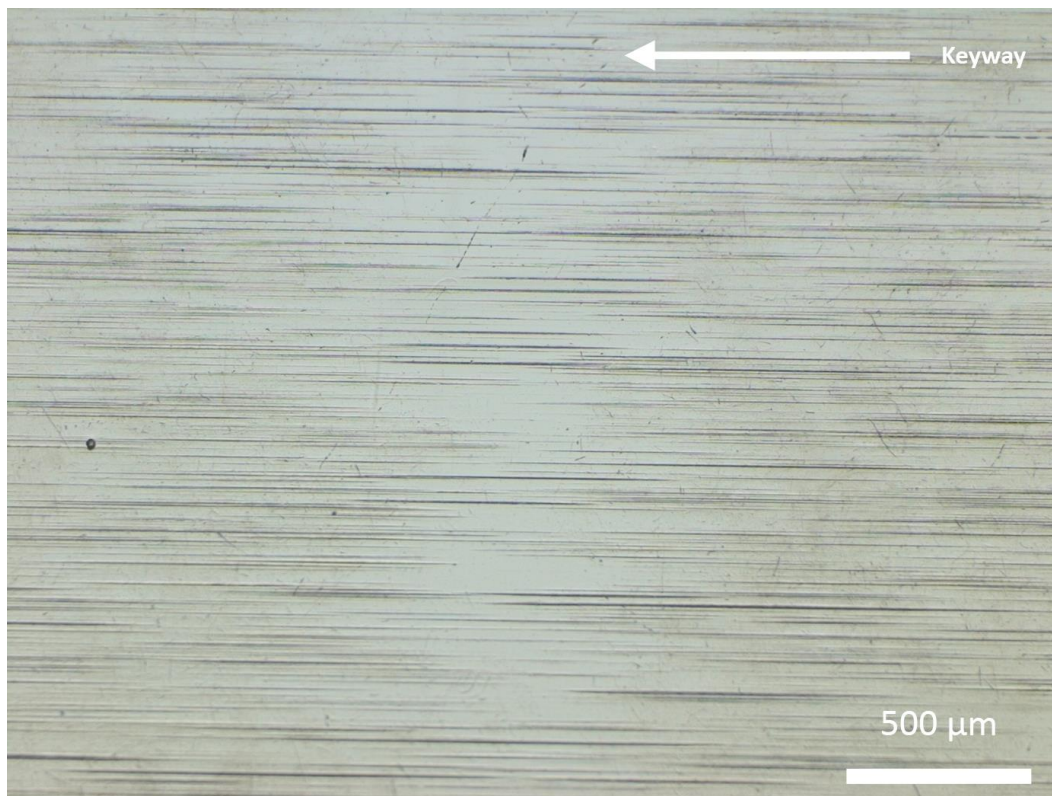


Figure 20. Bright-field optical micrograph of one of the flat faces of the cam ring from pump 4 (fuel 2, 1200 h).

The surface profile, shown in Figure 21 of pump 5, confirmed that the wear on the cam ring was low. The cam-ring surfaces retained a similar convex profile to the surface observed in the pristine pump (pump 1). The surface profile the oval-shaped

wear marking was difficult to discern visually. The roughness of the cam-ring surface was $Sa = 61 \pm 8$ nm. The pump 5 cam ring appeared to be the least run-in and thus was closest to the original roughness.

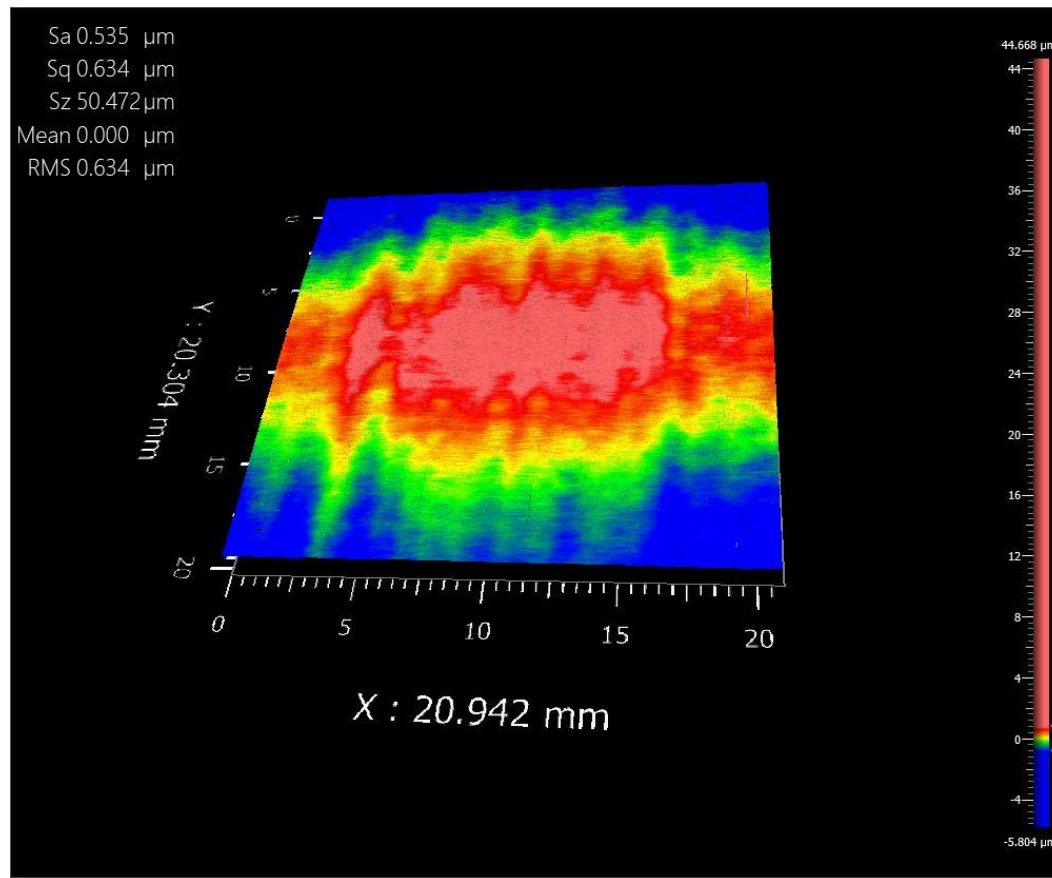


Figure 21. Surface profile of one of the flat faces of the cam ring from pump 5 (fuel 2, 1200 h).

3.2 Bucket

3.2.1 Pump 1 (0 h, Pristine)

The inward facing surface of the bucket, which contacted the cam ring, had an isotropic grind (Figure 22). The area surrounding the contact surface sloped upward from the contacting surface and had a circumferential grind. The curved side of the bucket contained a cylindrical grind, oriented perpendicular to the sliding direction of the bucket with the housing. The inside of the bucket contained a raised platform with an isotropic grind that contacts the plunger.

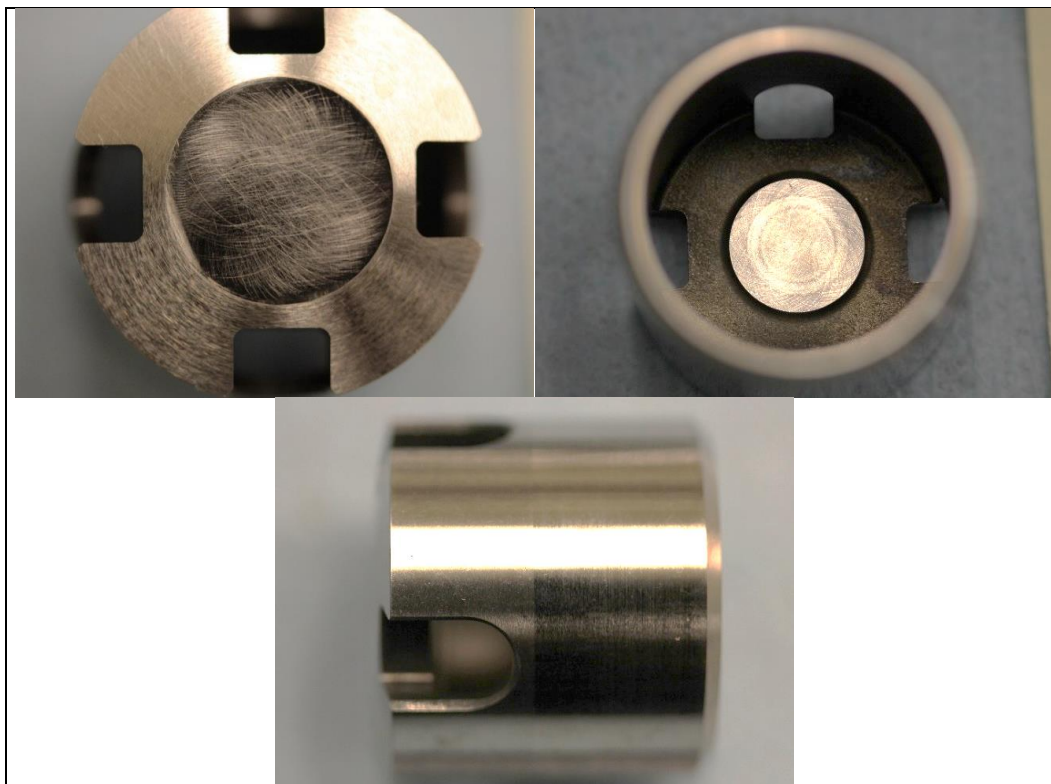


Figure 22. Bucket from pump 1 (pristine, 0 h).

The circumferential grind of the exterior curved surface can be seen as horizontal scratches at higher magnification in the left micrograph of Figure 23. The exterior flat surface contained scratches in every direction, characteristic of an isotropic grind. A few defects were observed on the surface, but they did not exceed 50 μm in width.

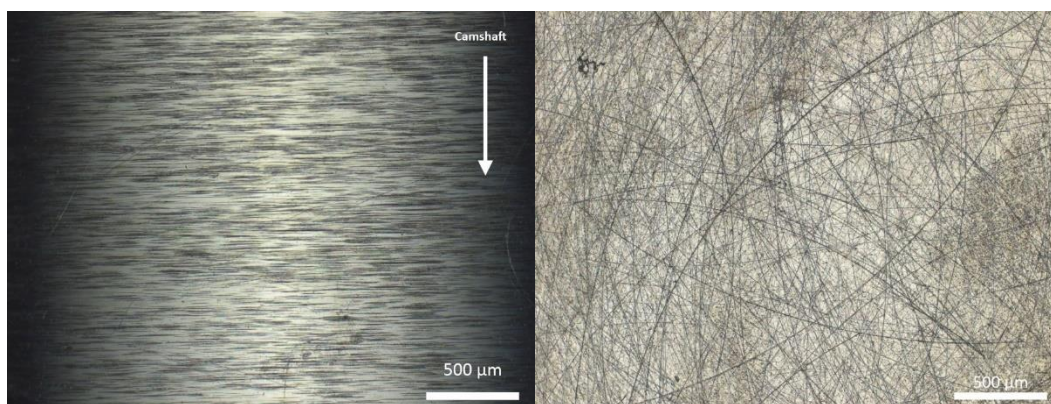


Figure 23. Bright-field optical micrographs of bucket from pump 1 (pristine, 0 h). Left, exterior curved surface; right, exterior flat surface.

A surface profile of the exterior flat surface in the bucket shows there was a slight concavity to the surface (Figure 24). The height varied by 2.0 μm across the

diameter of 11.5 mm. The roughness of the exterior flat surface was $S_a = 18 \pm 2$ nm. The profile of the interior raised platform (Figure 24) shows a similar concave profile with a height difference of $7.1 \mu\text{m}$ across a diameter of 8.4 mm. The roughness of the interior raised surface was $S_a = 81 \pm 16$ nm.

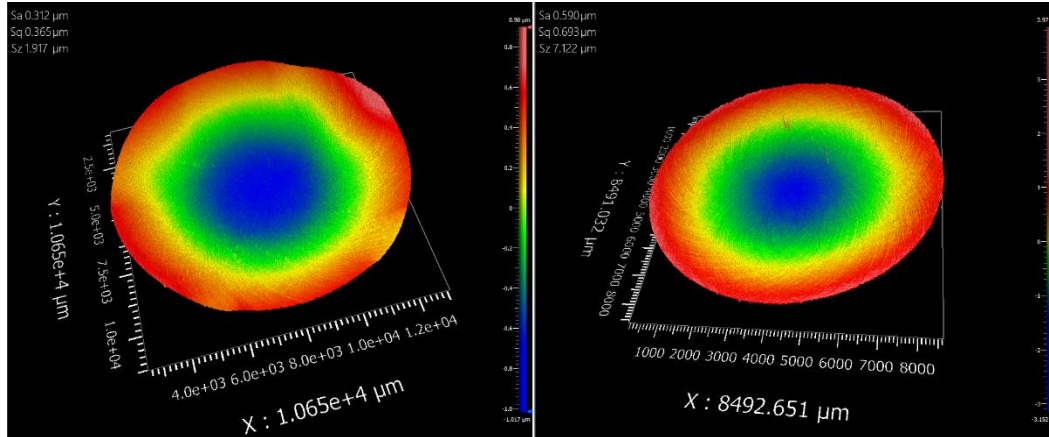


Figure 24. Surface profile of bucket from pump 1 (pristine, 0 h). Left, exterior flat surface; right, interior raised surface.

An SEM micrograph of the exterior curved surface of the pump 1 bucket is shown in Figure 25. The width of the grind marks was approximately 2 to 3 μm . The majority of the grind marks were oriented circumferentially (horizontal in the micrograph), but a few scratches ran in other directions. These scratches appeared to be of similar width to the grind marks.

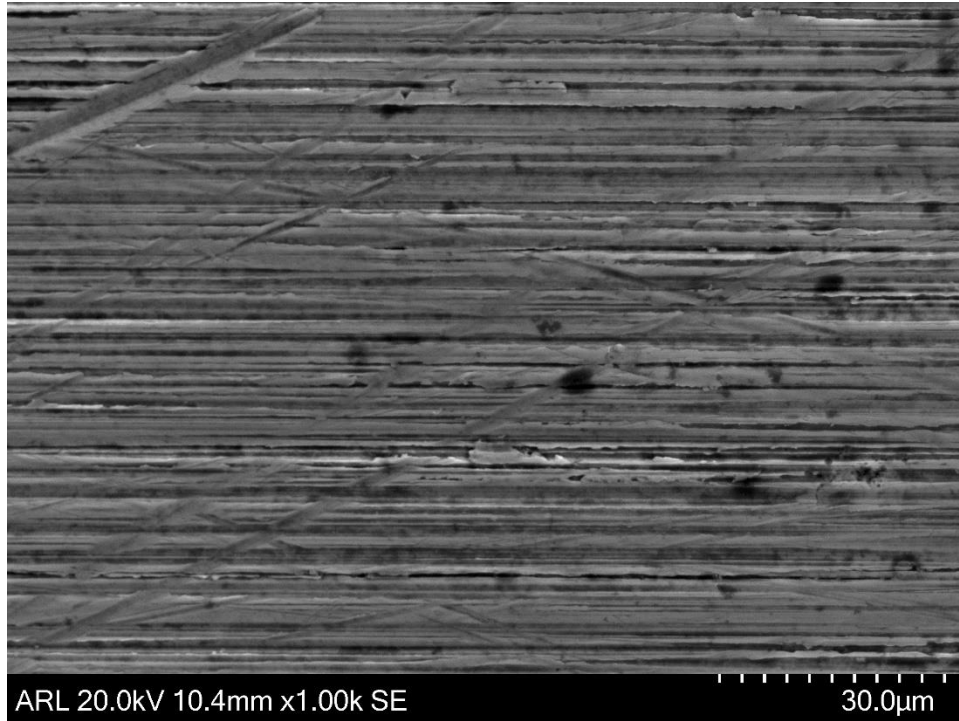


Figure 25. SEM micrograph taken with SE detector of exterior flat surface of bucket from pump 1 (pristine, 0 h).

The elemental composition of the bucket can be seen from the EDS spectra in Figure 26. The spectra shows that the bucket was predominantly iron with minor concentrations of chromium. Thus, the bucket was likely to be a low-alloy chrome steel such as AISI 52100.

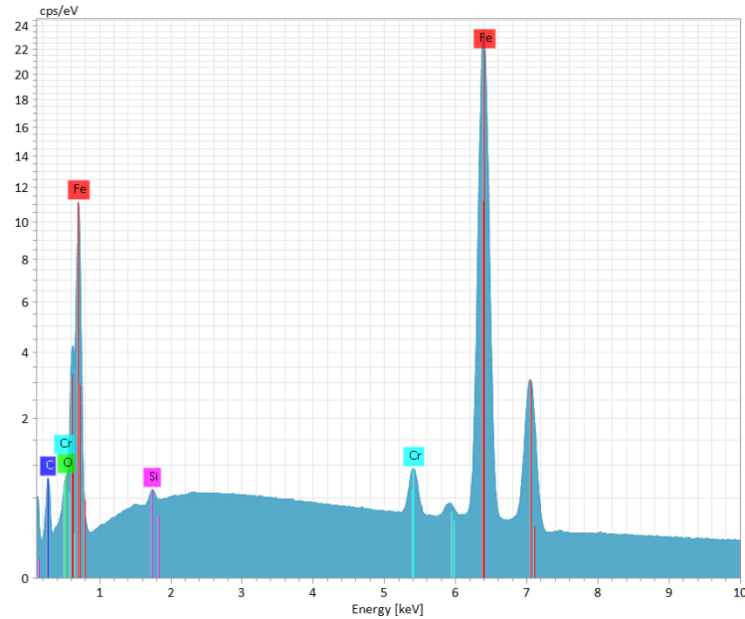


Figure 26. EDS spectra of exterior flat surface of bucket from pump 1 (pristine, 0 h).

The hardness of the top of the surface of the bucket was 61.4 ± 0.3 HRC and the hardness of the side surface was 61.6 ± 1.5 HRC.

3.2.2 Pump 2 (1052 h, Used until Inlet Clogged)

Wear was observed on the two exterior faces of the bucket and on the raised platform on the inside of the bucket (Figure 27). The exterior flat surface of the bucket had minimal wear as indicated by the presence of the original brushed finish in the center; however, there were some abrasive scratches observed towards the outer edges (Figure 27, upper left). On the inner surface, there was significant wear of the raise platform resulting in a change in the profile clearly visible by eye (Figure 27, lower center). The wear marks on the inner surface platform appeared to be oriented circumferentially, and the surface appeared more polished than that of pump 1. The wear on the curved surface of the exterior side extended around the entire circumference with a height of approximately 15 mm from the bottom edge (Figure 27, upper right). The wear appeared as discolored areas that had a shiny polished appearance, which indicated that the wear on this surface is most likely due to run-in.



Figure 27. Bucket from pump 2 (fuel 1, 1052 h).

Observation of additional details of the surfaces in the bright-field micrographs (Figure 28) revealed that two differences could be drawn between pumps 1 and 2 on the exterior curved surface. The first was that the surface of pump 2 appeared to have a much smoother appearance. The circumferential grind from the pristine bucket was absent from the pump 2 bucket. Instead, finer axial scratches were visible. The second difference was a color change. Patches of blue, brown, and dark matte grey were visible in pump 2 as opposed to the bright silvery grey in the pristine pump 1. The coloration of the surface was similar to tempered steel, which changes color due to thin film interference within a thin surface oxide film. This suggests that the surface may have tempered or formed a similar thin film from surface chemical interactions with the fuel. The micrograph of the exterior flat surface of the pump 2 bucket showed little difference from pump 1 except for the presence of dark-brown patches.

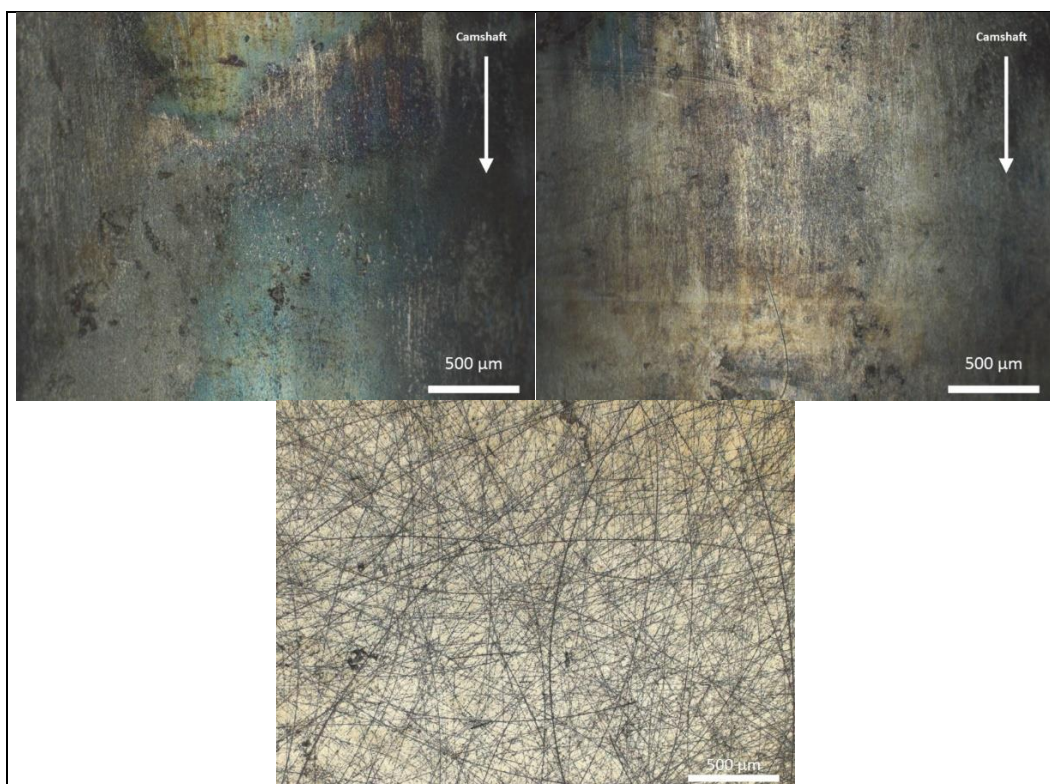


Figure 28. Bright-field optical micrographs of bucket from pump 2 (fuel 1, 1052 h). Left, exterior curved surface; center, exterior curved surface; right, exterior flat surface.

The surface profile of the exterior flat surface of pump 2 had minimal differences when compared with the profile of the pristine pump (Figure 29), except for some roughening of the surface. The height varied over a 2.0- μm range and mostly kept to the concave profile. The roughness of the exterior flat surface was $S_a = 23 \pm 7 \text{ nm}$. The surface profile of the interior raised surface was significantly altered by wear (Figure 29). The surface resembled a surface of revolution and there were many visible circumferential abrasive wear marks. The circumferential wear indicates the wear was likely due to rotation of the bucket relative to the plunger. The roughness of the interior raised surface was $S_a = 105 \pm 48 \text{ nm}$.

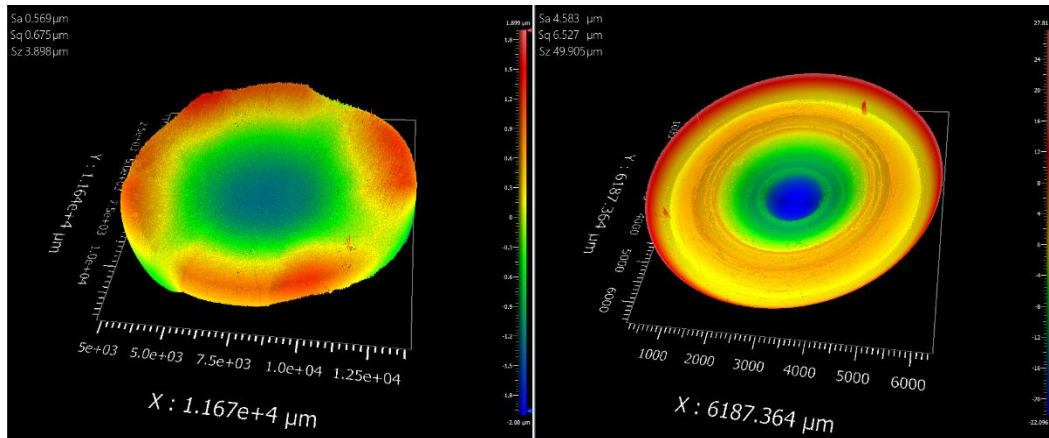


Figure 29. Surface profile of bucket from pump 2 (fuel 1, 1052 h). Left, exterior flat surface; right, interior raised surface.

3.2.3 Pump 3 (1800 h, Used until Inlet Clogged)

The bucket from pump 3 appeared to have wear similar to that of pump 2 (Figure 30). The exterior flat surface of the bucket was darker in color towards the edges (Figure 30, upper left). The number of scratches towards the center of the exterior flat surface appears to be greater in number than in the pristine pump. However, since the curvature was similar to the brushed finish observed in pump 1, it is likely that this surface of the bucket did not wear significantly. The raised platform on the inside of the bucket was worn in a similar way to pump 2 (Figure 30, lower center). The exterior curved surface of the bucket of pump 3 had more run-in than pump 2 as indicated by the increased size of the shiny patches (Figure 30, upper right). Similar to pump 2, this run-in did not appear to be a detriment to normal pump operation.



Figure 30. Bucket from pump 3 (fuel 1, 1800 h).

Bright-field micrographs of the bucket for pump 3 (Figure 31) showed many similarities to pump 2. The exterior curved surface (Figure 31, left) appeared to be smoother than in the pristine pump and had the same type of discoloration observed in pump 2. Pump 3 differed from pump 2 in that some of the circumferential grind marks present in the pristine surface were still visible for pump 3, suggesting that the surface had not worn as much as in pump 2, despite its longer run time. Such behavior is not unusual since the run-in process is usually dominated by conditions in the early stages of contact and does not alter the surface as significantly in the later stages. The exterior flat surface of the pump 3 bucket (Figure 31, right) had more brown discoloration than pump 2. In addition, the surface was worn slightly in certain spots, such as is seen in the bottom-left corner of the image of the exterior flat surface (Figure 31, right) where the isotropic grind marks were absent and several diagonal marks were present, all with the same direction. These marks suggest that mild abrasion of the surface took place.

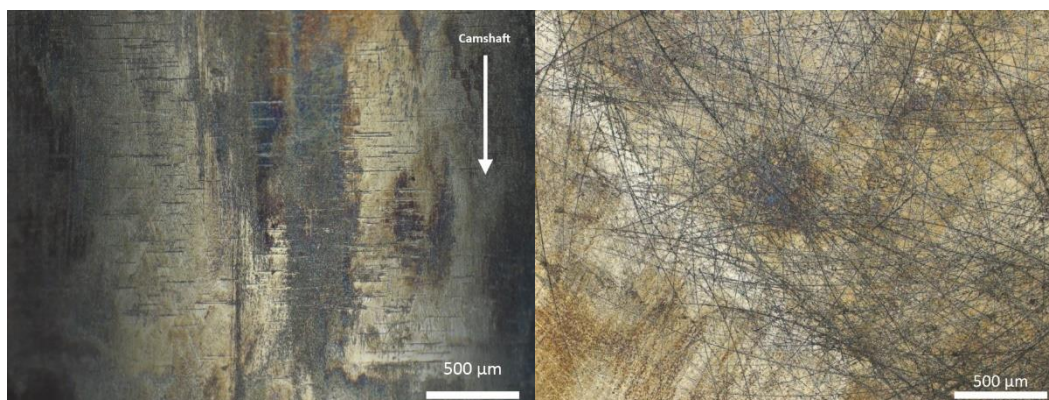


Figure 31. Bright-field optical micrographs of bucket from pump 3 (fuel 1, 1800 h). Left, exterior curved surface; right, exterior flat surface.

The surface profile of the pump 3 bucket (Figure 32) was similar to the profile for pump 2. The exterior flat surface had the same concave profile (Figure 32, left). The roughness of the exterior flat surface was $Sa = 41 \pm 17$ nm. The wear observed on the surface did not significantly alter the form of the surface. The profile for the interior raised surface in pump 3 (Figure 32, right) was similar to the profile in pump 2 in that both surfaces had circumferential wear marks that made the surfaces resemble bodies of rotation. However, the low point in the profile was in the center for pump 2, whereas the high point was in the center for pump 3. Therefore, the wear was not preferential to any specific portion of the surface between the two pumps. The roughness of the interior raise surface was $Sa = 423 \pm 196$ nm.

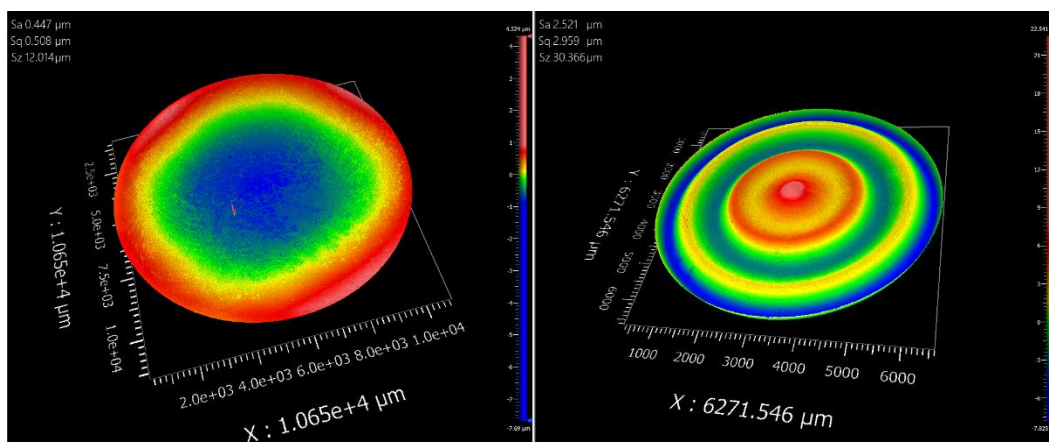


Figure 32. Surface profile of bucket from pump 3 (fuel 1, 1800 h). Left, exterior flat surface; right, interior raised surface.

The discolored region of the exterior curved surface of the pump 3 bucket was observed more closely with SEM (Figure 33). The surface was full of many small islands approximately 2 to 10 μm wide with flat tops. The islands may have formed due to the growth of solid deposit at several nucleation sites on the steel, while the flat tops were formed by wear of the top of the structure during sliding. The EDS

spectra of the surface revealed the major elements present are iron, carbon, and oxygen. The maps show oxygen is concentrated within the islands while the carbon was seen throughout.

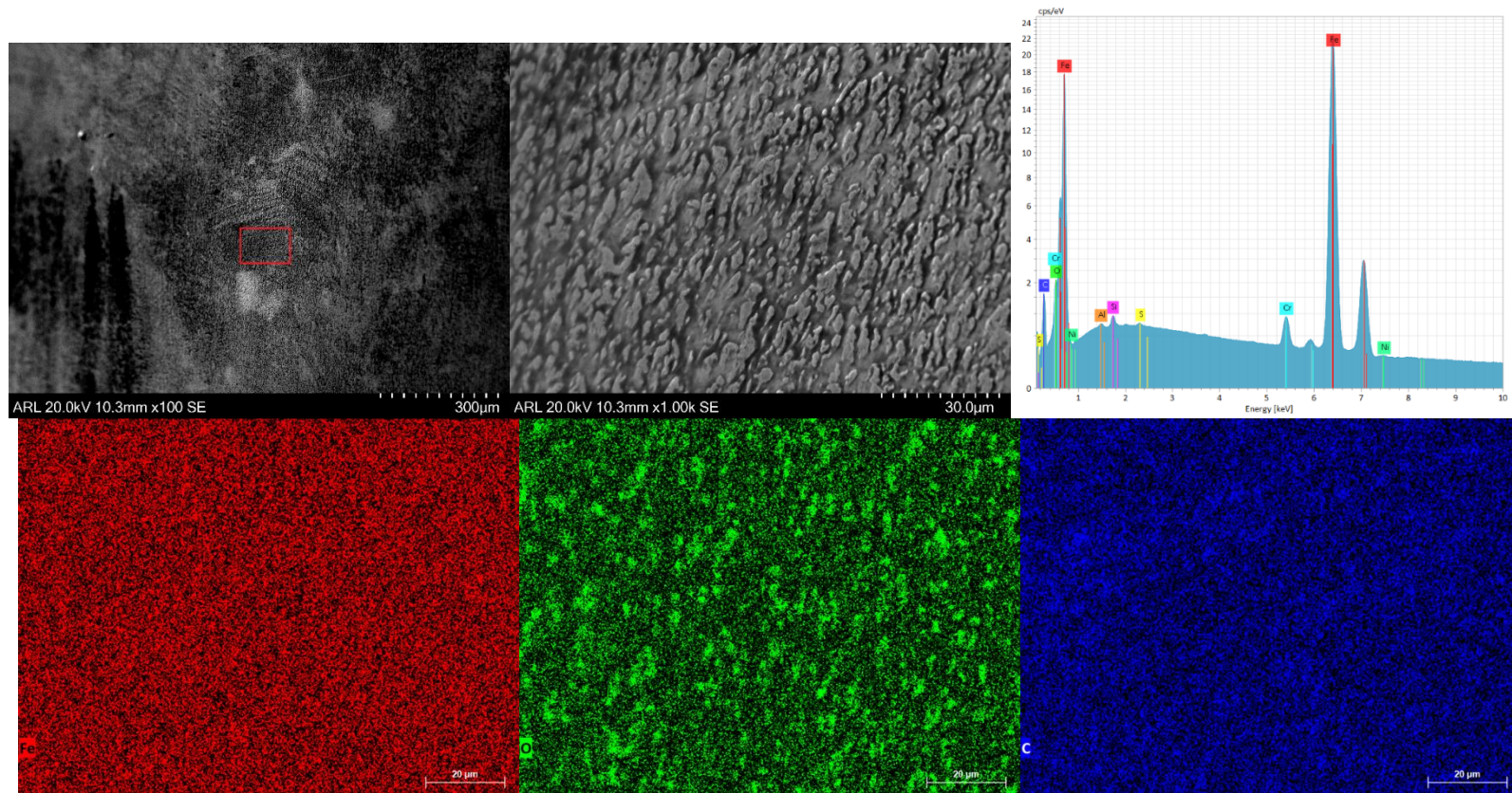


Figure 33. SEM micrograph taken with SE detector at 100× (top left) and 1000× magnification (top center), EDS spectra (top right), and EDS elemental maps at 1000× magnification of iron (bottom left), oxygen (bottom center), and carbon (bottom right) of the exterior curved surface on the bucket of pump 3 (fuel 3, 1800 h).

3.2.4 Pump 4 (476 h, Failure due to Plunger Seizure)

The pump 4 bucket is shown in Figure 34. Some discoloration was observed on the exterior curved surface and the ring outside of the exterior flat surface, but there was significantly less discoloration overall for pump 4 than for pumps 2 and 3. Some scratches were seen on the exterior curved surface as well as a few marks on the exterior flat surface.



Figure 34. Bucket from pump 4 (fuel 2, 476 h).

Optical micrographs of the exterior curved surface show these features more closely (Figure 35). A slight discoloration was seen on the exterior curved surface (Figure 35, left). Additionally, there were several scratches on the plunger oriented along the axis of the pump bore. These scratches were likely abrasive wear marks from the bucket sliding against the pump bore. The exterior flat surface had many randomly oriented scratches, which appear similar to the original isotropic grind (Figure 35, right).

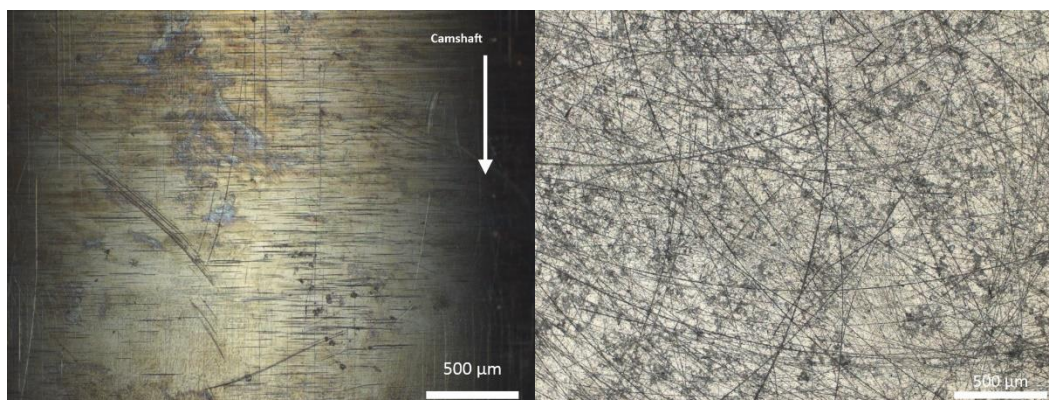


Figure 35. Bright-field optical micrographs of bucket from pump 4 (fuel 2, 476 h). Left, exterior curved surface; right, exterior flat surface.

The surface profile of the pump 3 bucket is shown in Figure 36 and had a similar appearance to the other pumps. The exterior flat surfaces had the same concave profile (Figure 36, left). The roughness of the exterior flat surface was $S_a = 41 \pm 7$ nm. The wear observed on the surface did not significantly alter the form of the surface. The profile for the interior raised surface had a prominent convex curvature with a few radial scratches (Figure 36, right). Similar to pumps 2 and 3, the pump 4 surface resembles a surface of revolution. However, the circumferential grooves due to wear were located at a different radius, as with the other pumps. The roughness of the interior raise surface was $S_a = 249 \pm 82$ nm.

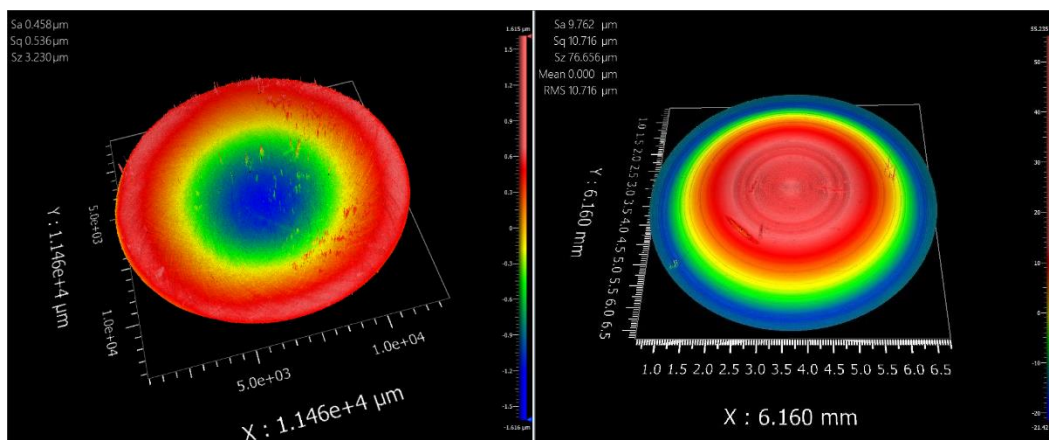


Figure 36. Surface profile of bucket from pump 4 (fuel 2, 476 h). Left, exterior flat surface; right, interior raised surface.

3.2.5 Pump 5 (1200 h, Failure due to Plunger Seizure)

The bucket from pump 5 had a shiny metallic appearance (Figure 37) similar to the pristine pump. The exterior flat surface had several abrasive scratches running unidirectionally (Figure 37, upper left) as opposed to the isotropic grind in the pristine pump. The five divots visible on the flat surface were due to hardness measurements conducted after operation of the pump. The interior raised surface had some circumferentially oriented scratches (Figure 37, center). The exterior curved surface of the bucket had a ring towards the inward facing edge which appeared less worn than the surrounding surface (Figure 37, upper right). This portion of the pump does not contact the housing during operation of the pump. At the boundary between this portion of the surface and the contacting surface, there appeared to be slight discoloration, but it was less than the surfaces in pumps 2 and 3.



Figure 37. Bucket from pump 5 (fuel 2, 1200 h).

Bright-field micrographs of the bucket show that the exterior curved surface of the bucket from pump 5 (Figure 38, left) kept many of the same features observed in the pristine pump. The circumferentially oriented grind marks were still visible. There appeared to be a few randomly oriented scratches and some small patches of discoloration, but these compromised a small portion of the surface. The isotropic grind was still visible on the exterior flat surface of the bucket (Figure 38, right).

This suggests that there may have been some abrasive wear on the bucket. These abrasive scratches appeared to be the same size as the original grind.

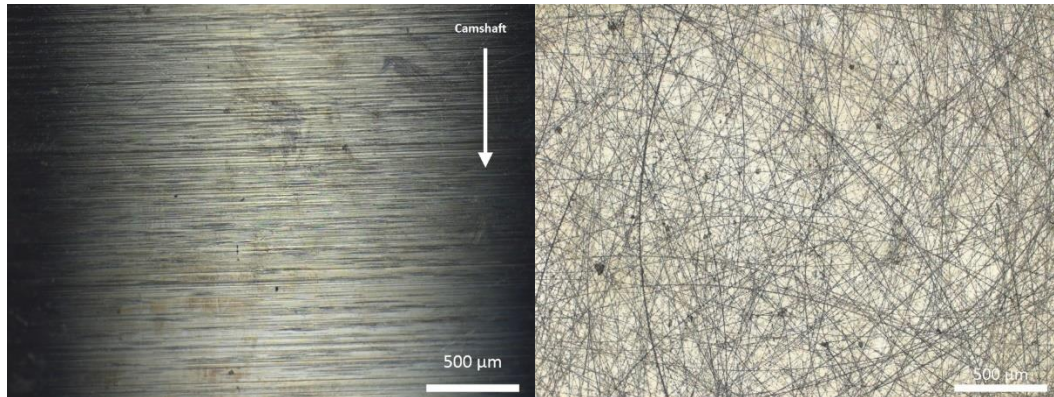


Figure 38. Bright-field optical micrographs of bucket from pump 5 (fuel 2, 1200 h). Left, exterior curved surface; right, exterior flat surface.

The surface profile of the pump 5 bucket is shown in Figure 39. The exterior flat surfaces had the same concave profile (Figure 39, left). The roughness of the exterior flat surface was $S_a = 38 \pm 12$ nm. There was not a significant difference to the other pumps in the form of the surface. The profile for the interior raised surface also resembled a surface of revolution (Figure 39, right) with a unique circumferential radial wear pattern as the other pumps. The roughness of the interior raise surface was $S_a = 581 \pm 302$ nm.

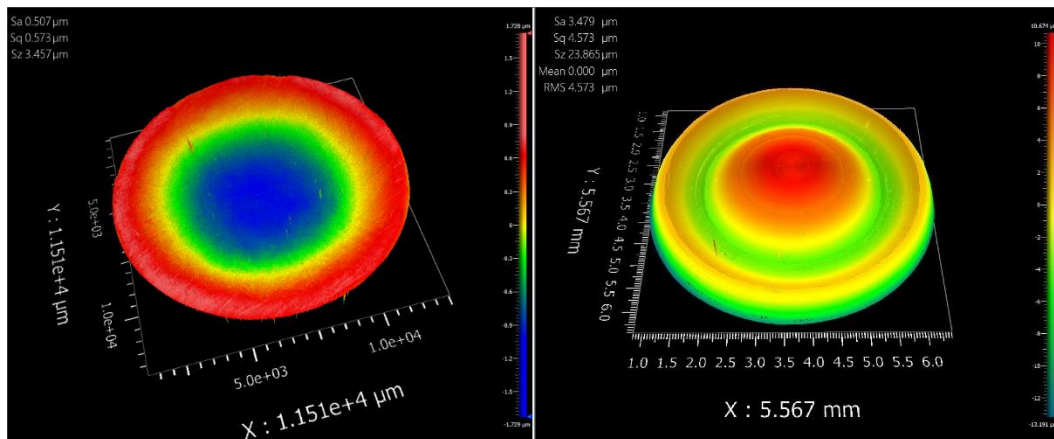


Figure 39. Surface profile of bucket from pump 4 (fuel 2, 1200 h). Left, exterior flat surface; right, interior raised surface.

3.3 Plunger

3.3.1 Pump 1 (0 h, Pristine)

The plunger contained three sections. It had a flat base which contacts the bucket on the inward facing side and plunger return spring on the other side, a cylindrical

middle section that contacts the housing, and a conical head that fits onto the inlet valve spring (Figure 40). The base of the plunger contained a raised platform with a circular brushed finish that contacted with the raised platform in the bucket. The cylindrical section had a circumferential surface grind that was oriented perpendicular to the direction of sliding with the housing.

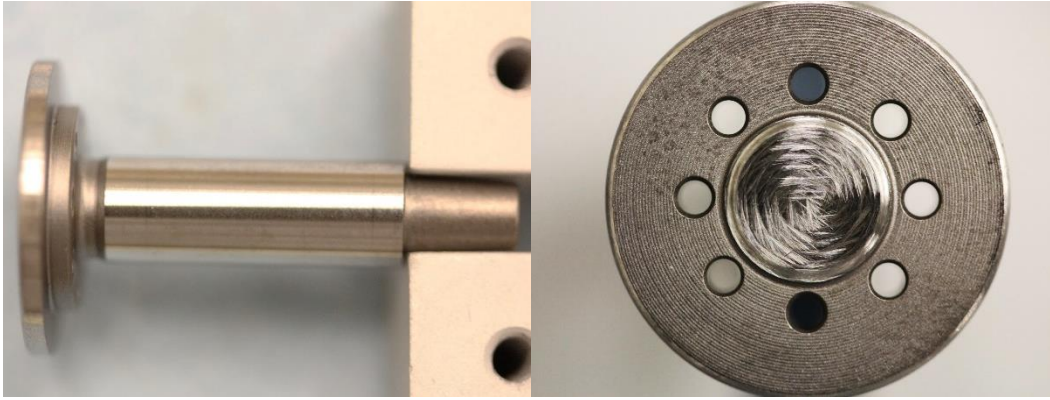


Figure 40. Plunger from pump 1 (pristine, 0 h).

The circumferential grind on the plunger shaft can be seen in more detail in the bright-field micrograph (Figure 41, left). A few defects were observed on the surface but they did not exceed 50 μm in width, nor were they enough to obscure the grind marks (Figure 41, right). The plunger base had a rough brushed finish made of short, linear scratches perpendicular to the center point (Figure 41, right).

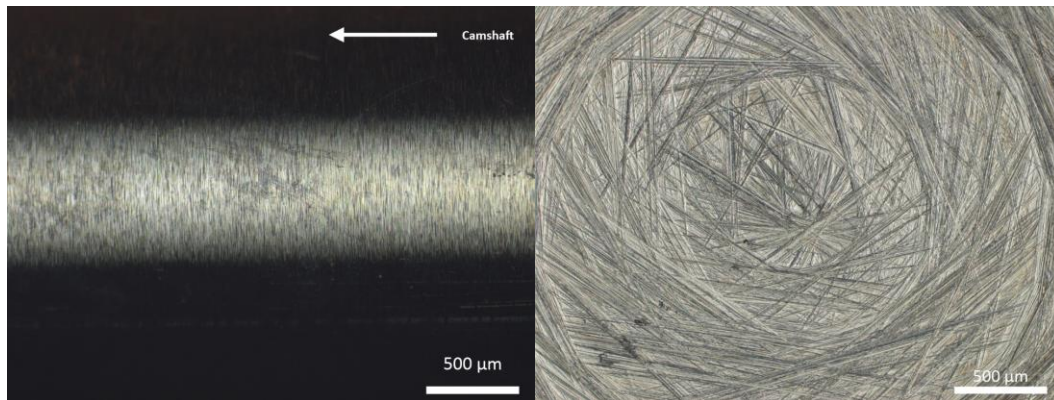


Figure 41. Bright-field optical micrographs of plunger from pump 1 (pristine, 0 h). Left, shaft; right, base.

A close-up surface profile of a portion of the plunger base reveals the cross-hatched scratches from the brushed finish (Figure 42). The raised portion of the base of the plunger had a convex profile with a height variation of approximately 7 μm over a width of 5.7 mm. The roughness of the plunger base was $S_a = 358 \pm 148 \text{ nm}$. The roughness of the plunger shaft was $S_a = 46 \pm 8 \text{ nm}$.

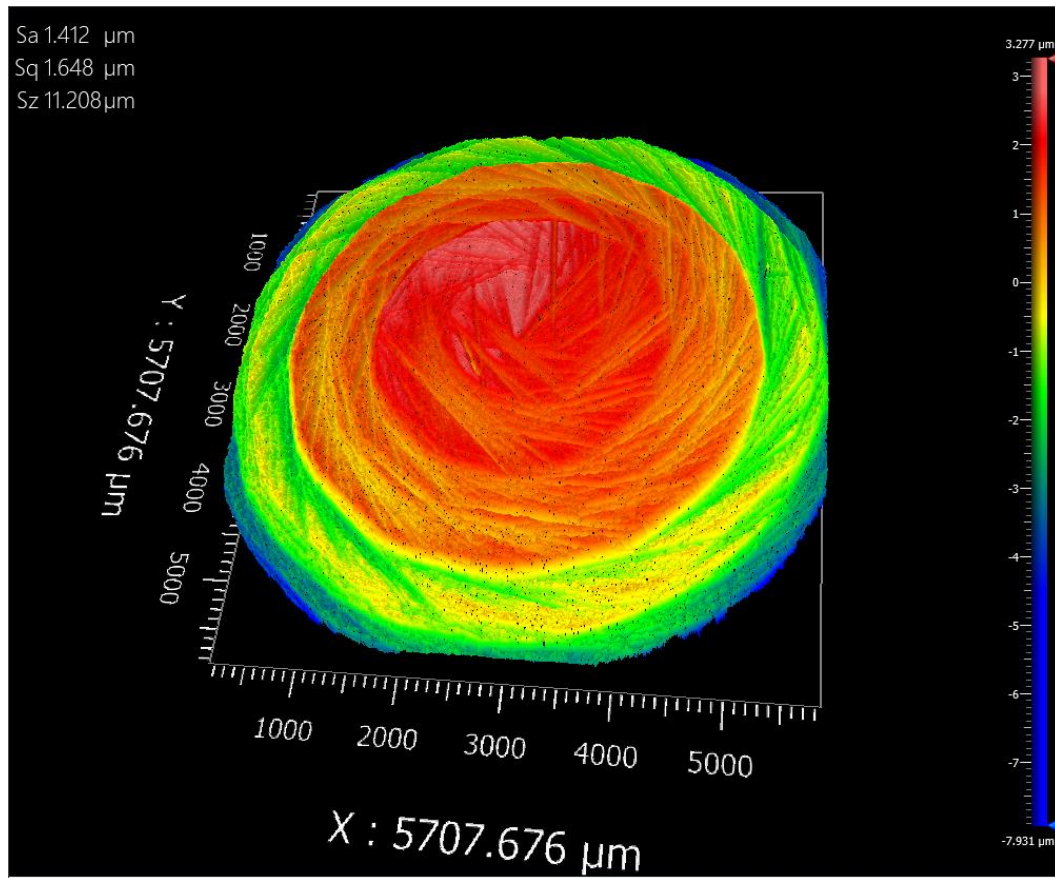


Figure 42. Surface profile of plunger base from pump 1 (pristine, 0 h).

The SEM micrograph in Figure 43 shows the circumferentially oriented grind of the plunger shaft going from the top left to the bottom right of the micrograph. The grind marks were approximately 2 to 5 μm wide.

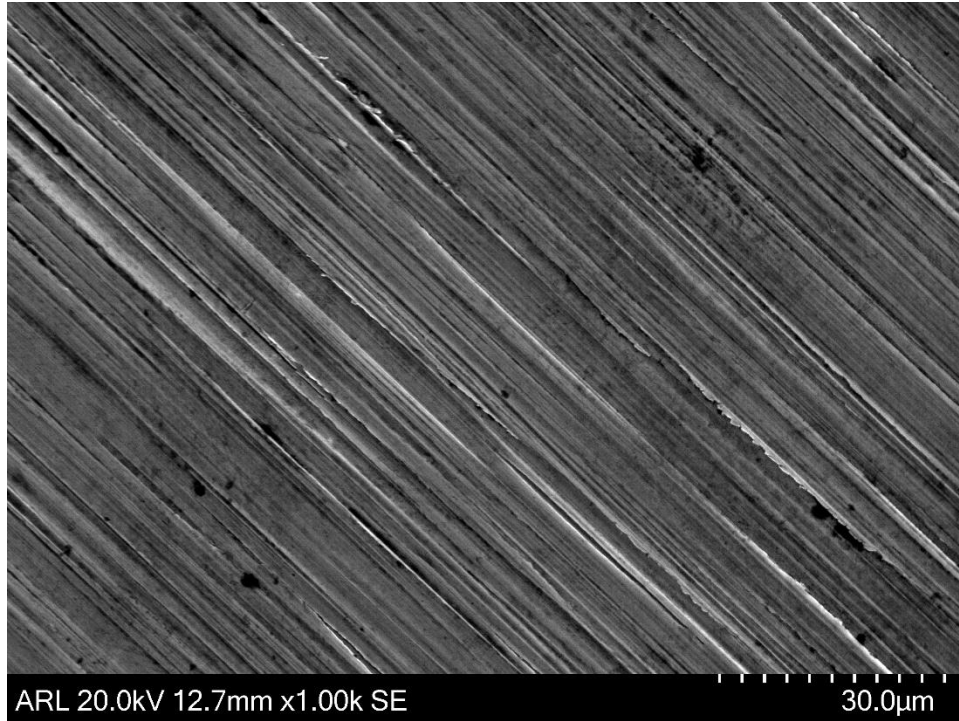


Figure 43. SEM micrograph taken with SE detector of the plunger shaft from pump 1 (pristine, 0 h).

The elemental composition of the plunger can be seen from the EDS spectra in Figure 44. The spectra shows that plunger was predominantly iron with small quantities of chromium, nickel, copper, aluminum, and silicon. The aluminum and silicon signals may have come from the plunger material or from the vacuum chamber and EDS detector, respectively. Thus, the plunger is likely to be a low-alloy chrome steel such as AISI 52100.

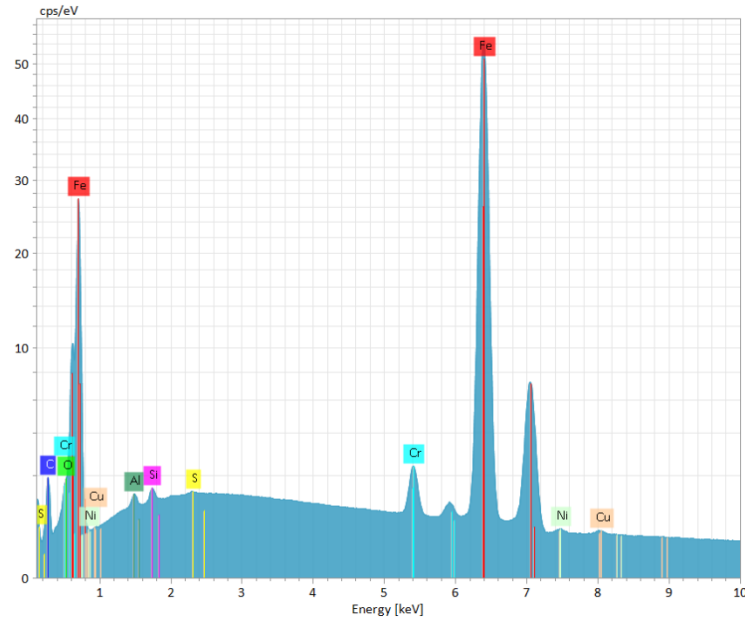


Figure 44. EDS spectra of the plunger shaft from pump 1 (pristine, 0 h).

3.3.2 Pump 2 (1052 h, Used until Inlet Clogged)

Wear was observed along the central shaft and the raised surface on the bottom face of the plungers of pump 2 (Figure 45). The wear on the raised surface was enough to visibly remove the surface finish. The wear marks primarily appear to be oriented axially, and the surface appeared shinier and more polished. The wear on the shaft of the plunger appeared along the entire length and around the entire circumference; however, the overall shape did not appear significantly altered. In addition, the pump 2 plunger had areas colored brown and dark blue as opposed to the silvery metallic color of the pristine plunger. There appeared to be several abrasive marks oriented along the axial direction covering up the original circumferential grind.

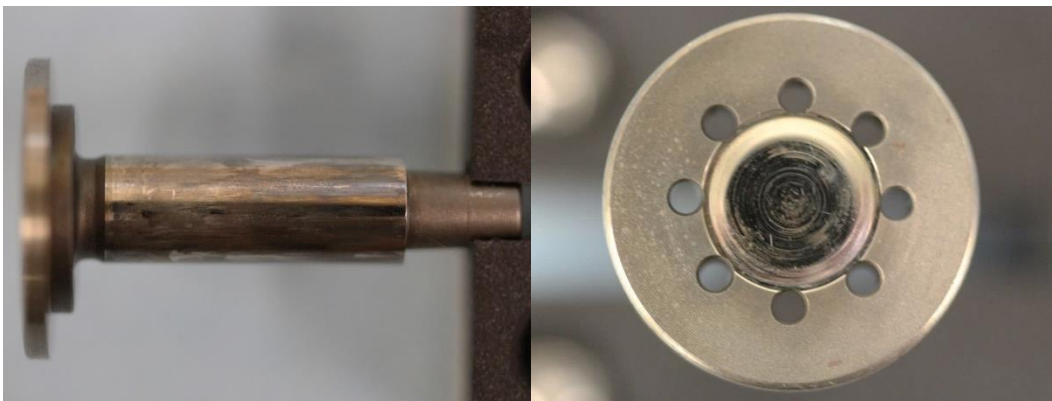


Figure 45. Plunger from pump 2 (fuel 1, 1052 h).

Bright-field micrographs of the cylindrical portion of the plunger show the discoloration and wear in more detail (Figure 46, left). The discoloration in the plunger was similar to that of the bucket, where it was suspected that the coloring was caused by thin film interference from tempering of the steel or film formation from surface chemical interactions with the fuel. Figure 46 also shows how the surface texture had been altered. Only small portions of the original circumferential grind were visible. The deepest portions of these grind marks appeared to be the only areas where the metallic color of the pristine plungers was still visible. Much of the other area appeared to be smoothed out; however, there were also many primarily axially oriented scratches. This was likely caused by abrasive third-body wear, either from particulates in the fuel or wear debris from other portions of the pump. In pump 5 below, fine silica particles were observed to be embedded at the end of similar scratches in the plunger. The plunger base was much smoother in appearance with some grooves in the shape of concentric circles (Figure 46, right).

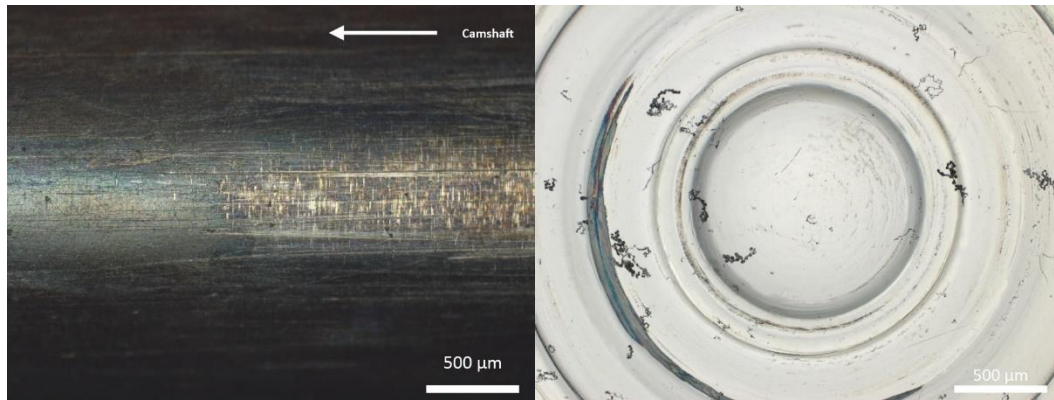


Figure 46. Bright-field optical micrographs of plunger from pump 2 (fuel 1, 1052 h). Left, shaft; right, base.

The profile of the base of the plunger (Figure 47) revealed a wear pattern with circumferentially oriented abrasive wear marks, which made the surface resemble a surface of revolution. When compared with the profile of the interior raised surface of the pump 2 bucket, the plunger surface appeared to be the inverse pattern, having high points corresponding to low areas on the bucket. These two surfaces must be rotating relative to each other during operation, causing this circular wear pattern. The surfaces conform to each other to minimize local stresses between the mating surfaces. The roughness of the plunger base was $S_a = 146 \pm 190$ nm. The roughness of the plunger shaft was $S_a = 82 \pm 16$ nm. The used plunger shaft was rougher than the pristine plunger due to the presence of the axially aligned abrasive marks.

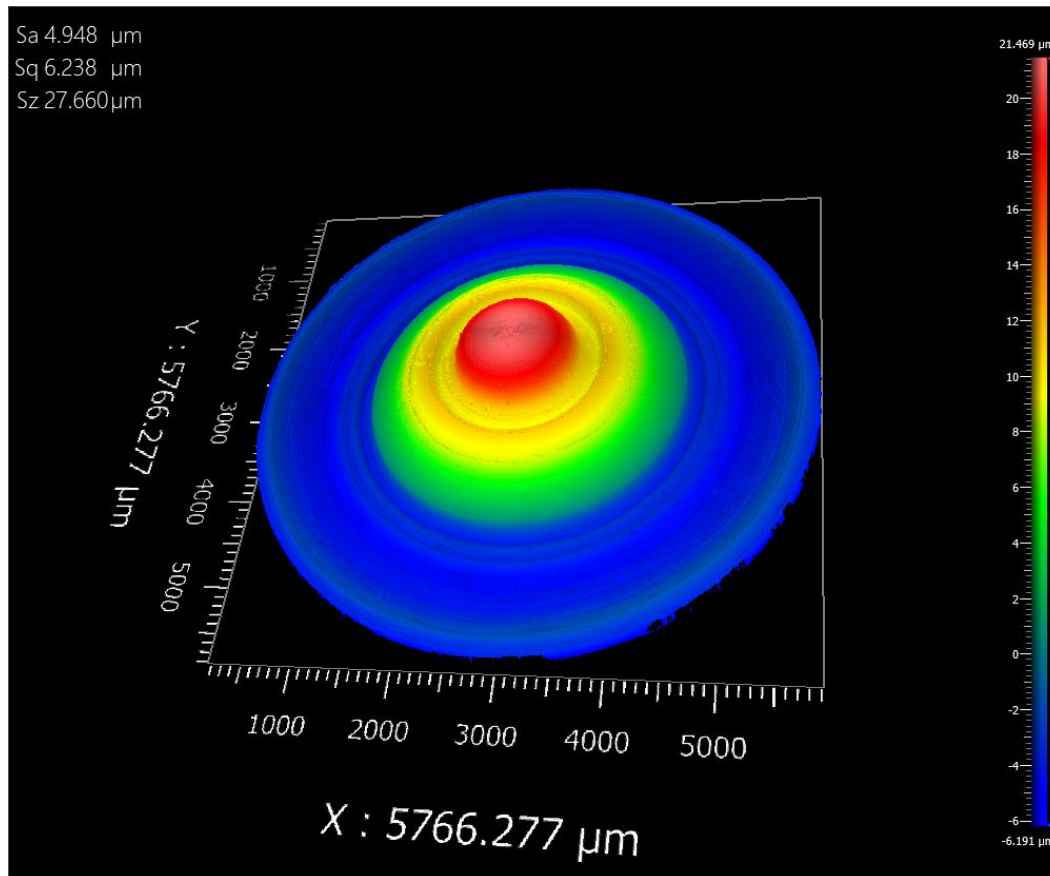


Figure 47. Surface profile of plunger base from pump 2 (fuel 1, 1052 h).

The hardness of the plunger was 60.2 ± 1.4 HRC.

3.3.3 Pump 3 (1800 h, Used until Inlet Clogged)

The plungers from pump 3 had several dark markings and several axially oriented scratches (Figure 48). This appearance was similar to the plunger of pump 2 and matched the discoloration seen in the pump 3 bucket. Lastly, the plunger contained wear on the outer portion of the raised platform at the base where the plunger contacts the bucket. The wear on the plungers appeared to match the wear on the buckets.

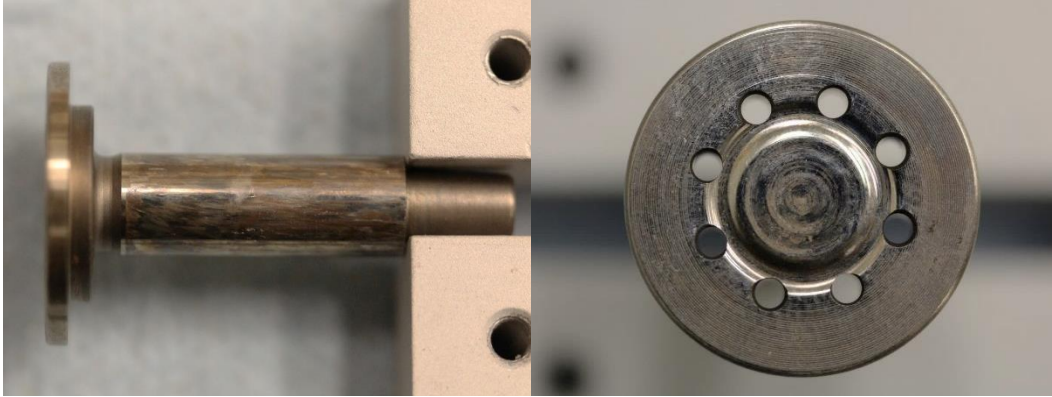


Figure 48. Plunger from pump 3 (fuel 1, 1800 h).

Bright-field micrographs of the plunger show the surface of the plunger in more detail (Figure 49). The majority of the surface was covered in the same dark-colored areas that were prominent in pump 2. The pump 3 plungers had more abrasive scratches than the pump 2 plungers. The scratches were primarily axially oriented, but many had some circumferential component. There were some areas where the discoloration is not present, as seen in the center of the left micrograph of Figure 49. The plunger base (right) had a slight brown discoloration with many dark-grey spots speckled across the surface.

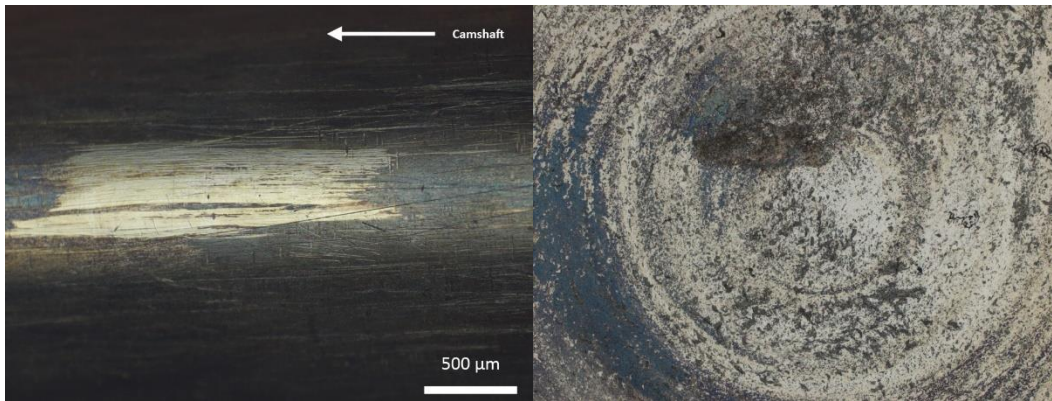


Figure 49. Bright-field optical micrographs of plunger from pump 3 (fuel 1, 1800 h). Left, shaft; right, base.

A surface profile of the base of the pump 3 plunger (Figure 50) revealed a wear pattern with circumferentially oriented wear marks, which made the surface resemble a surface of revolution. When compared to the profile of the interior raised surface of the pump 3 bucket, the plunger surface appeared to be the inverse pattern, having high points corresponding to low areas on the bucket. Similar to pump 2, the surfaces appeared to wear due to rotation of the bucket and plunger with respect to each other. By comparing the surfaces in pump 2 and 3, it can be seen there was some variability in the wear patterns indicating no location on the surface has

preferential wear. The roughness of the plunger base was $S_a = 561 \pm 274$ nm. The roughness of the plunger shaft was $S_a = 73 \pm 29$ nm.

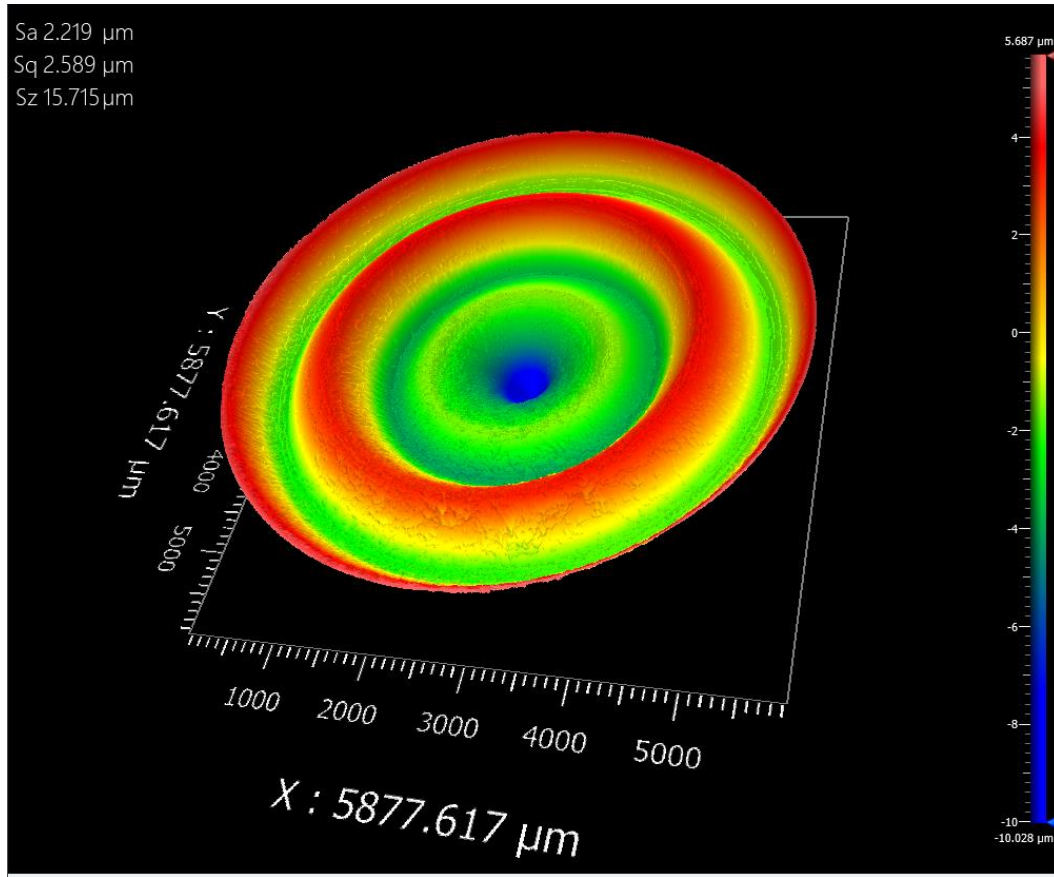


Figure 50. Surface profile of plunger base from pump 3 (fuel 1, 1800 h).

The SEM micrographs (Figure 51) of the pump 3 plunger showed there were small pits that had formed on the plunger surface. These pits were approximately 20 to 40 μm wide. The EDS spectra (Figure 50) showed that the composition was mostly iron with small amounts (<10%) of chromium and oxygen. The oxygen was observed in a much smaller quantity for the plunger than for the bucket.

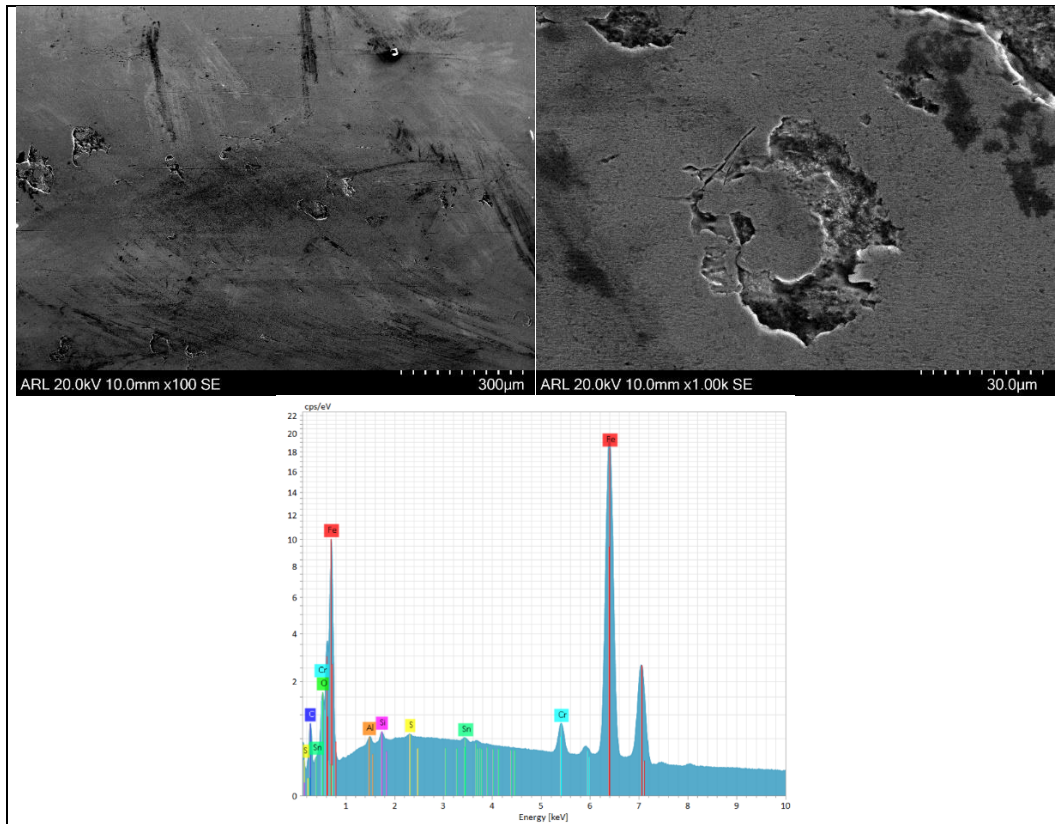


Figure 51. SEM micrograph taken with SE detector at 100× (upper left) and 1000× magnification (upper right) and EDS spectra (center) of the plunger from pump 3 (fuel 3, 1800 h).

3.3.4 Pump 4 (476 h, Failure due to Plunger Seizure)

The pump 4 plungers had significantly less discoloration than pumps 2 and 3 (Figure 52). Two marks were seen on the plunger, one near the tip and another towards the base. There were some circular wear marks on the base of the plunger.

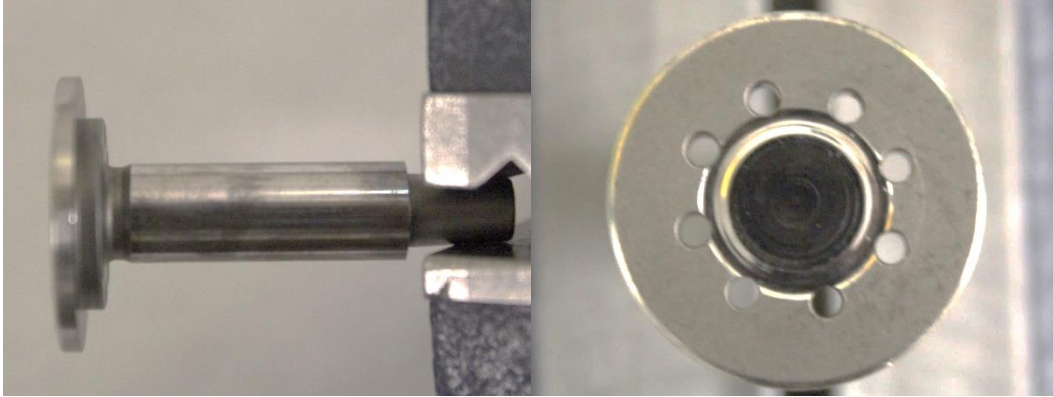


Figure 52. Plunger from pump 4 (fuel 2, 476 h).

Optical micrographs of the plunger are shown in Figure 53. The plunger had some patches of discoloration, although significantly less than in pumps 2 and 3. Several scratches were oriented primarily along the axial direction, suggesting that there may have been some abrasive wear, possibly from third-body particles. The plunger base was mostly smooth with some concentric grooves. A few brown spots were visible.

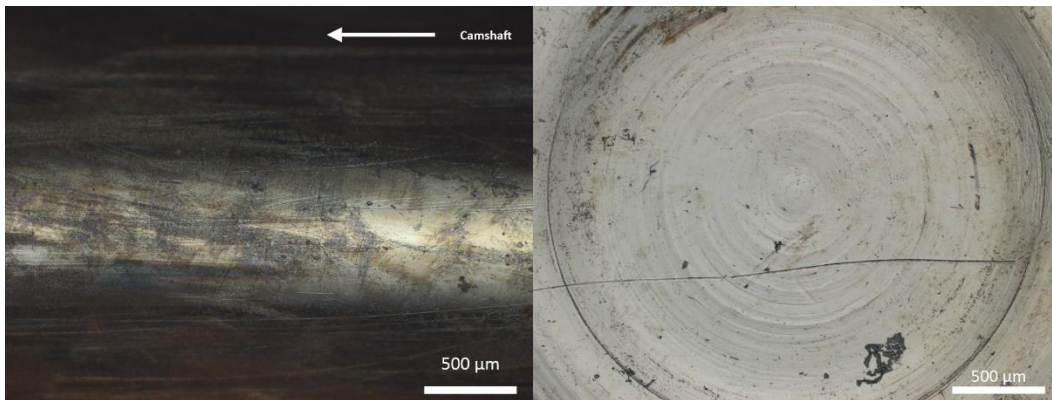


Figure 53. Bright-field optical micrographs of plunger from pump 4 (fuel 2, 476 h). Left, shaft; right, base.

A surface profile of the pump 4 plunger is shown in Figure 54. Similar to the other pumps, the pump 4 plunger had a wear pattern that appeared to be the reflection of the complementary surface in the bucket. The surface resembled a surface of revolution. The roughness of the plunger base was $S_a = 249 \pm 82$ nm. The roughness of the plunger shaft was $S_a = 72 \pm 10$ nm.

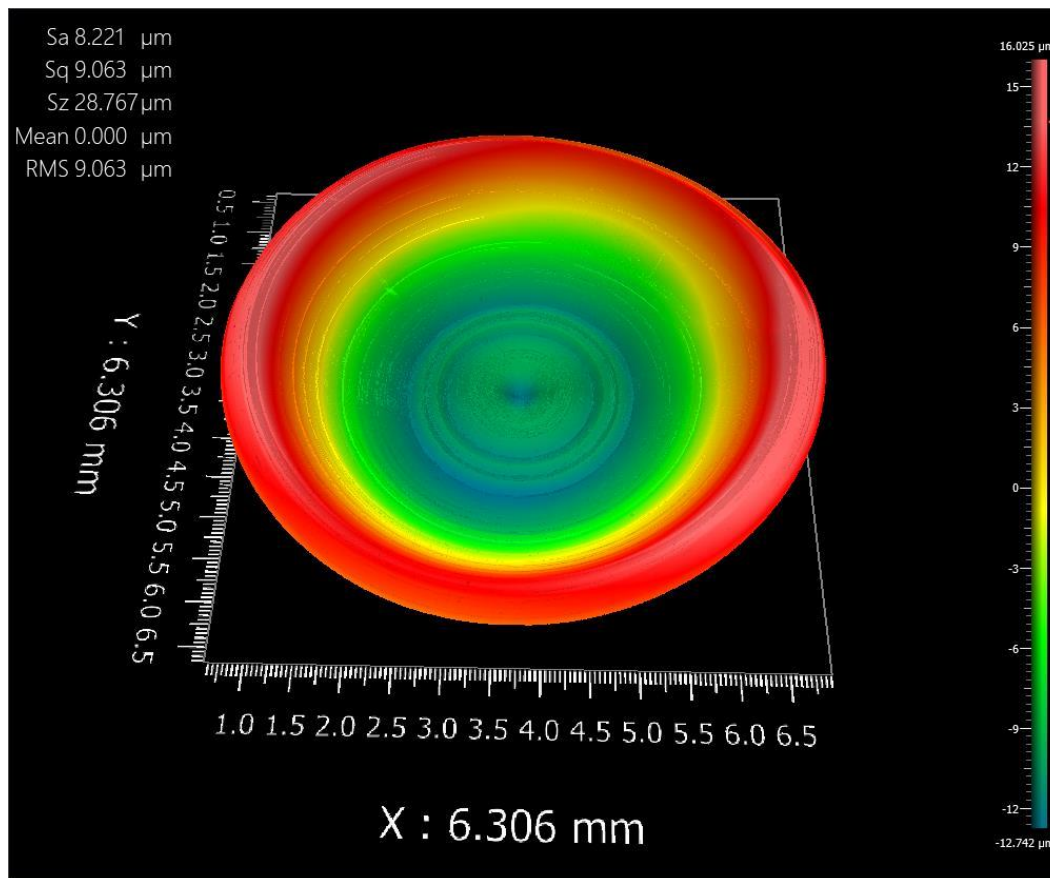


Figure 54. Surface profile of plunger base from pump 4 (fuel 2, 476 h).

3.3.5 Pump 5 (1200 h, Failure due to Plunger Seizure)

In pump 5, the plungers displayed some discoloration towards the base of the plunger where it contacted the edge of the housing bore. One of the plungers had a large area displaying scuffing damage on the surface, shown on the left of Figure 55. Scuffing is generally characterized by sudden and severe irreversible roughening and wear of the surface through gross plastic deformation of surface material and adhesion of counterface material. We conclude that the wear was due to scuffing because of the abrupt boundary between the scuffed and unscuffed surfaces and due to the very minor amount of wear in the unscuffed region. The base of the plunger had circumferentially oriented scratches and minor discoloration. The increase in plunger dimensions through scuffing was likely the cause for the seizure of the plunger and decrease in flow rate.

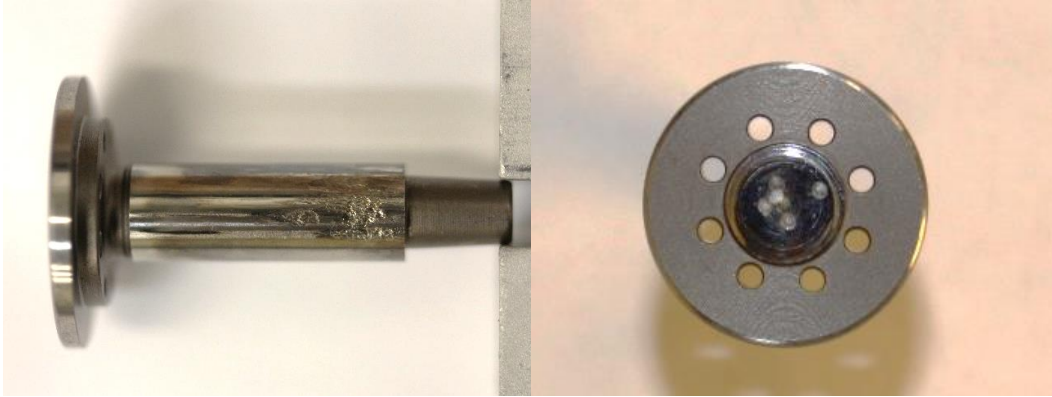


Figure 55. Plunger from pump 5 (fuel 2, 1200 h).

The bright-field micrographs of the plunger (Figure 56) show the details of the surface. The micrograph of the cylindrical portion of the plunger on the left of Figure 56 shows an unsuffed area on the upper left of the micrograph and a scuffed area on the right. In the unsuffed area, much of the original circumferentially oriented surface grind was visible. The surface had some discoloration, but it was much less than in the pump 2 and 3 plungers. This discoloration was limited to what appears to be the high points of surface, leaving the deepest crevices unchanged. In the scuffed area, the surface had large amounts of material removed and redeposited, which resulted in a significantly rougher appearance. Similar to the unsuffed surface, the scuffed area only had minor discoloration, limited to small areas of the surface. The plunger base had the same circular pattern as seen in pumps 2 and 4. Additionally, a few brown–grey spots were located on the surface.

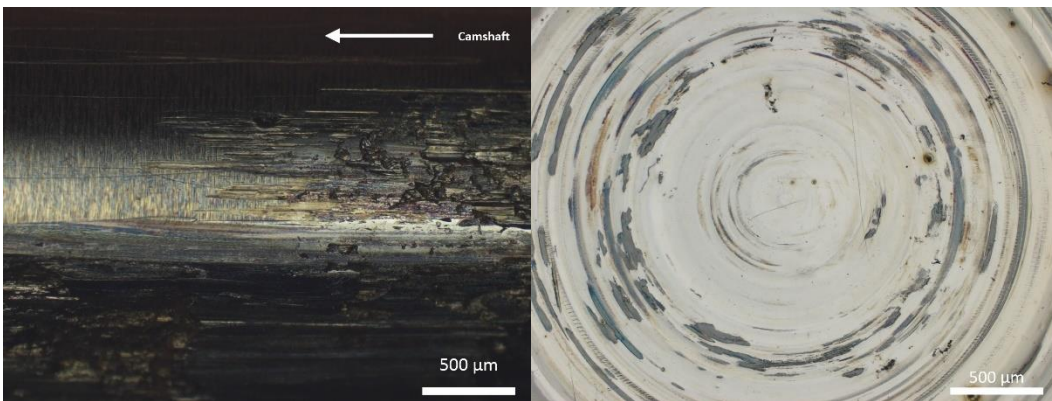


Figure 56. Bright-field optical micrographs of plunger from pump 5 (fuel 2, 1200 h). Left, shaft; right, base.

The surface profile of the plunger 5 base is shown in Figure 57. The profile of the plunger base had a similar wear to that seen in the other pumps. The roughness of the plunger base was $S_a = 581 \pm 302$ nm. The pump 5 plunger had significant scuffing on part of the shaft, which resulted in much higher roughness within the

scuffed area. The roughness of the plunger shaft was $S_a = 109 \pm 8$ nm outside of the scuffed area and $S_a = 4896 \pm 3394$ nm within the scuffed area. The roughness outside of the scuffed area was higher than the pristine plunger shaft due to the large amount of abrasive marks.

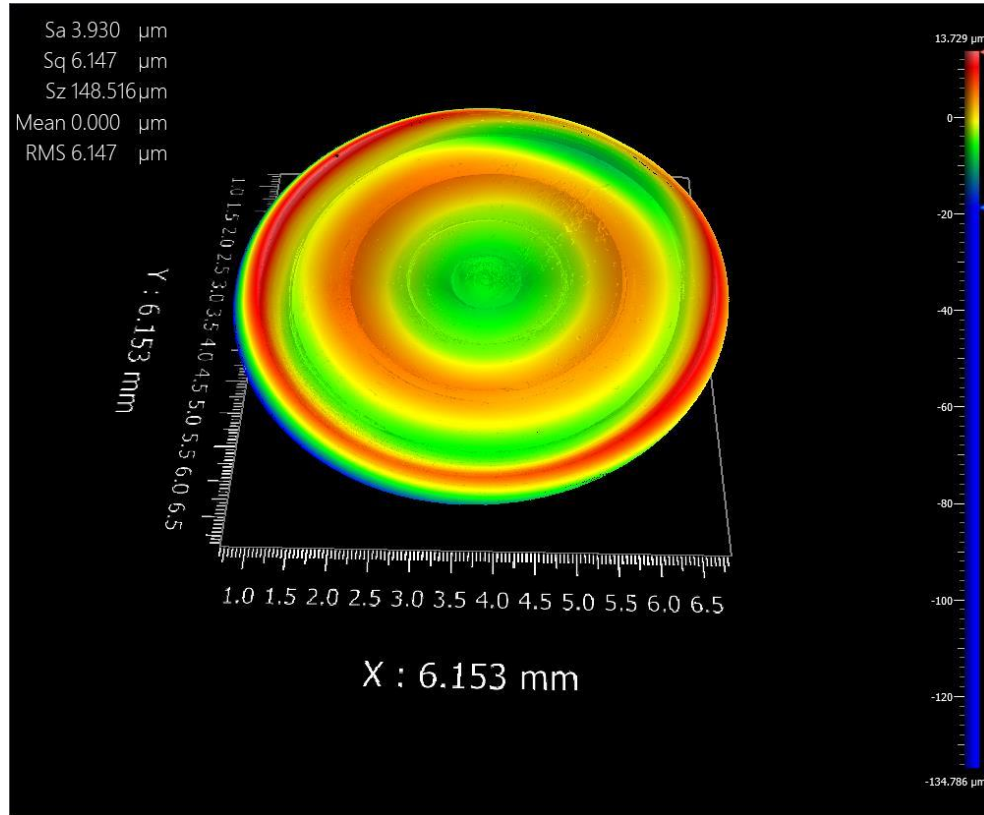


Figure 57. Surface profile of plunger base from pump 5 (fuel 2, 1200 h).

The scuffed area of the cylindrical portion of the plunger was observed with SEM (Figure 58). The SEM micrograph in the top left of Figure 58 shows the change in topography and roughness between the scuffed region on the left side of the micrograph and the unscuffed region on the right side. An EDS spectrum of the full micrograph (Figure 58, top right) shows that there was little oxygen present. Further inspection of the scuffed area using EDS maps shows no significant difference in oxygen content between the scuffed and non-scuffed regions. Localized heating during sliding of steel against steel often results in the formation of iron oxides that protect the surface from the initiation and/or spread of scuffing.²⁶ The small amount of oxides observed in the EDS spectrum suggested that little oxygen was present in the system to form a protective layer against scuffing, which is likely due to the lack of air in the interior of the pump when filled with fuel.

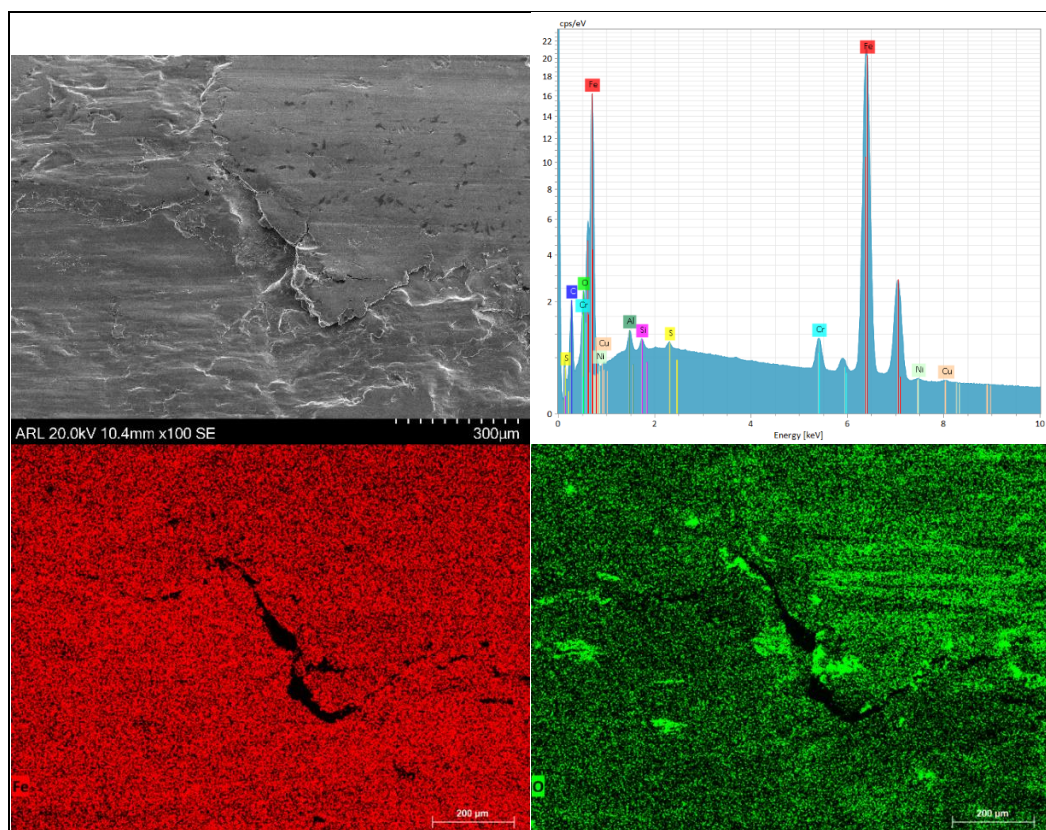


Figure 58. SEM micrograph taken with SE detector (top left), EDS spectra (top right), and EDS elemental maps of iron (bottom left), oxygen (bottom right) of scuffing on the plunger shaft from pump 5 (fuel 2, 1200 h).

Closer observations of the long, axially oriented scratches in the unscuffed region were made for pump 5 with SEM and EDS in Figure 59. Often particles were embedded at the ends of the scratches, as seen in the SEM micrograph in the top left of Figure 59. When observed with EDS, these particles were found to be rich in silicon and oxygen (for example, the spectrum at top right is from the red-boxed region of the micrograph), far beyond the silicon and oxygen concentrations found in the overall SEM micrograph (spectrum at top center). The EDS maps in the lower three panels of Figure 59 show that the silicon signal was localized only to the area at the end of the scratch and is colocated with an increased oxygen concentration. This means that the abrasive scratches were caused by third-body abrasion from silica particulate contaminants in the fuel. The particles and abrasions left behind were often 2 μm in width and up to 6 μm in width towards the ends, which is near the size of the 2- μm filter used on the pump stand. These abrasions may have caused the initial surface degradation and localized concentration of surface stress that led to the scuffing of the surface.

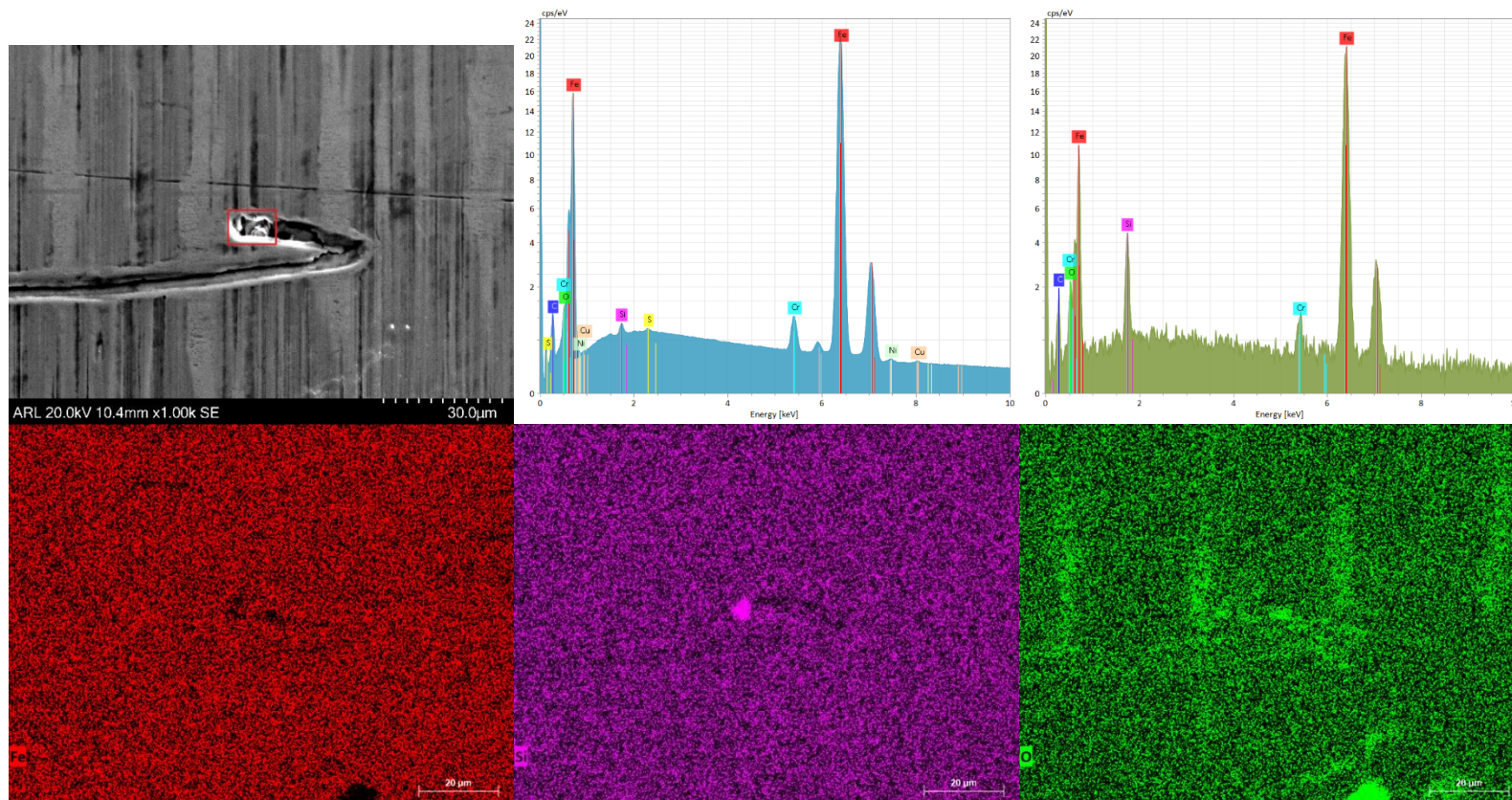


Figure 59. SEM micrograph taken with SE detector (top left), EDS spectra of the full area (top center), boxed particle (top right), and EDS elemental maps of iron (bottom left), silicon (bottom center) and oxygen (bottom right) of a particle on the plunger shaft from pump 5 (fuel 2, 1200 h).

3.4 Valves

3.4.1 Pump 1 (0 h, Pristine)

Figure 60 contains photographs of the inlet suction valve and outlet check valve. The inlet valve (Figure 60, left) has a narrow cylindrical section attached to a wider conical section. The cylindrical section is oriented towards the outside of the pump and sits within a bore in the inlet valve seat (Figure 60, center), while the conical section sits towards the inside of the pump oriented towards the plunger bore. The inlet valve seat has a cylindrical bore in the center with three notches towards the sides. The notches give the bore a clover-like shape. The inlet valve seat also has a conical incline away from the bore for the valve to sit flush against. When the valve is open, the fluid is allowed to move within the notches in the bore to get around the cylindrical portion of the valve, then in the gap between the conical portions of the valve and valve seat (Figure 61). When the valve is closed, the conical portions of the valve and valve seat form a seal to prevent inlet fuel flow during the high-pressure pump stroke. The pristine outlet valve (Figure 61, right) was a ball with an isotropic tumbled finish. The ball sits in a conical seat within the housing of the pump. Photographs were not taken of the outlet valve seat due to the difficulty of viewing it through the narrow passages.



Figure 60. Inlet suction and outlet check valves from pump 1 (pristine, 0 h). Left, inlet suction valve; bottom center, inlet valve seat; right, check valve ball.

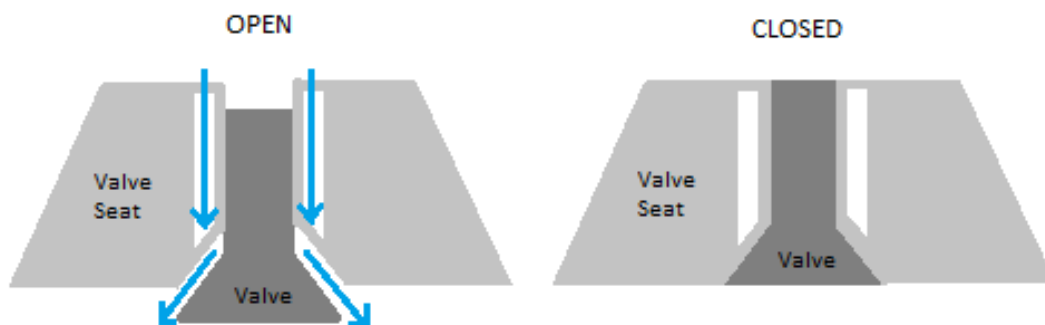


Figure 61. Fuel flow past the inlet valve and inlet valve seat in the open and closed positions.

The surface finish can be seen more clearly in the bright-field optical micrographs of the valves and valve seat (Figure 62). The conical and cylindrical portions of the inlet valve (Figure 62, bottom left and top left) appeared to have an isotropic surface finish. A ring was observed next on the conical section where it mated with the inlet valve seat, as pointed out by the red arrow. The inlet valve seat (Figure 62, center) had a cylindrical grind within the inside conical surface that mates with the inlet valve. The outside of the inlet valve seat (Figure 62, top right) appeared to have a rough isotropic surface finish. The curvature from the center edge of the valve seat bore can be seen at the top left of the micrograph and one of the notches can be seen towards the center. The outlet check valve ball (Figure 62, bottom right) displayed a smooth surface with a uniform isotropic finish. A few 20 μm pores were visible on the ball.

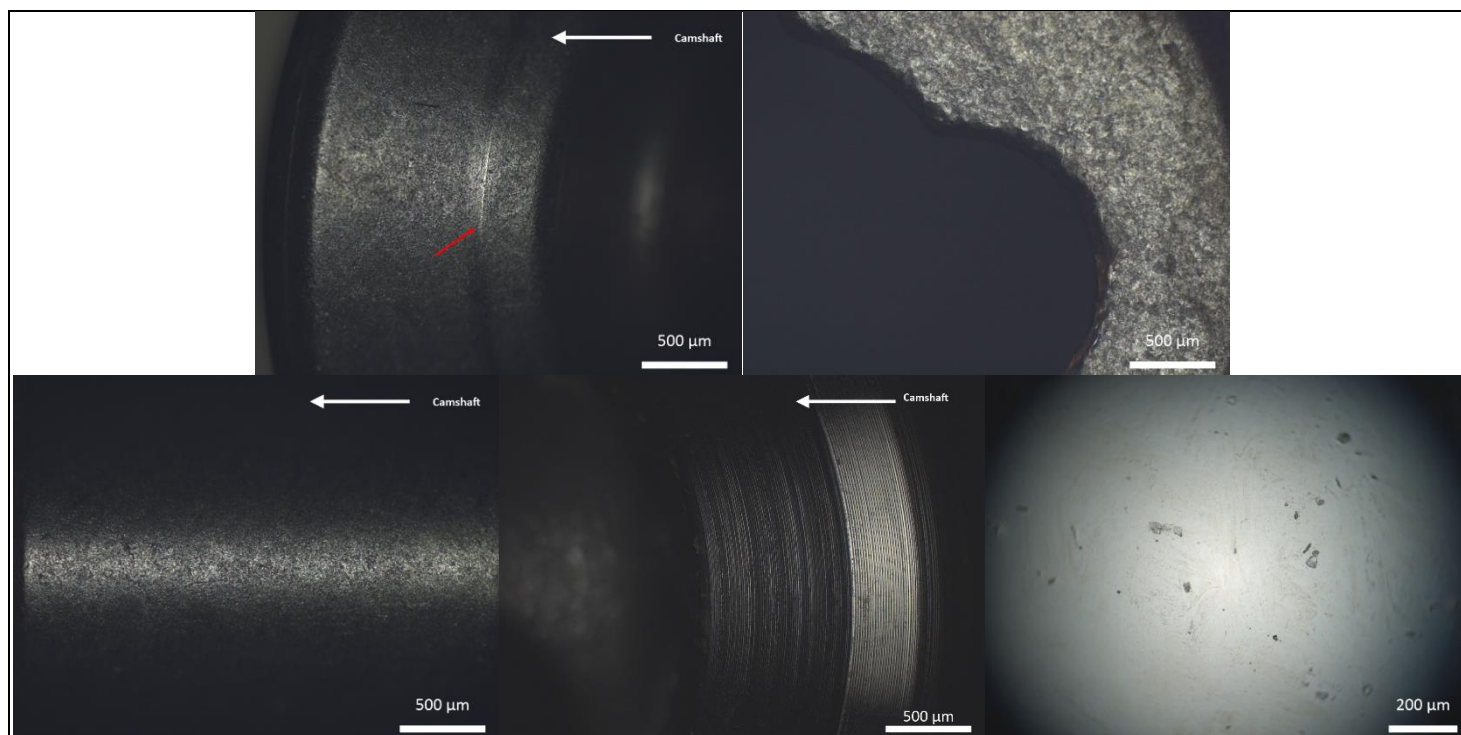


Figure 62. Bright-field optical micrographs of inlet suction and outlet check valves from pump 1 (pristine, 0 h). Bottom left, conical section of inlet suction valve; top left, cylindrical section of inlet valve; bottom center, inside of inlet valve seat; top right, outside of inlet valve seat; bottom right, check valve ball.

The hardness of the inlet valve seat was 59.6 ± 1.0 HRC. The hardness of the inlet valve and outlet valve were not measured due to the size of the component.

3.4.2 Pump 2 (1052 h, Used until Inlet Clogged)

In pump 2, several minor changes were observed in the inlet and outlet valves and inlet valve seat, however the forms of these components did not appear to have changed in a significant manner (Figure 63). The tips of the cylindrical portion of the inlet valves (Figure 63, left) appeared to be more polished, and there were some axially oriented abrasive marks along the tips. No significant change in the surface topography appeared further towards the base of the inlet valve of the conical portion. The inlet valve seat (Figure 63, center) similarly had not shown any significant signs of wear. The only observation was of some residue trapped in one of the inlet channels. The outlet valves (Figure 63, right) had discoloration of the surface, but there did not appear to be a significant change in roughness or form.



Figure 63. Inlet suction and outlet check valves from pump 2 (fuel 1, 1052 h). Left, inlet suction valve; bottom center, inlet valve seat; right, check valve ball.

The changes in the valves and valve seat can be seen more closely in the bright field optical micrographs in Figure 64. The left-most micrograph shows the inlet check valve towards the tip of the cylindrical portion. The surface appeared to be relatively unchanged away from the tip and towards the conical section. The surface appeared to be smoother at the tip except for a small area that appeared scuffed. The scuff was approximately 0.2 mm wide and 1 mm long. Since the cylindrical portion of the inlet valve was not the sealing interface in the valve, it was unlikely to interfere with the function of the valve. However, the conical portion of the inlet valve is critical since it forms a sealing surface with the inlet valve seat. The conical portion of the inlet valve had many circumferentially oriented abrasive marks. This is likely due to wear from rotation of the valve relative to the valve seat during operation. Both the inlet valve and valve seat were free to rotate about their center axis. The inside of the inlet valve seat had several circumferentially oriented

abrasive marks, which appeared to be wider and deeper than the original grind, and a slight rainbow coloration was observed. The outside inlet valve seat appeared to be the same as it was in the pristine pump. The outlet check valve had patches on the surface that appeared discolored in a similar manner to the bucket and plungers from the pump, but the surface profile appeared to be mostly the same as in the pristine pump.

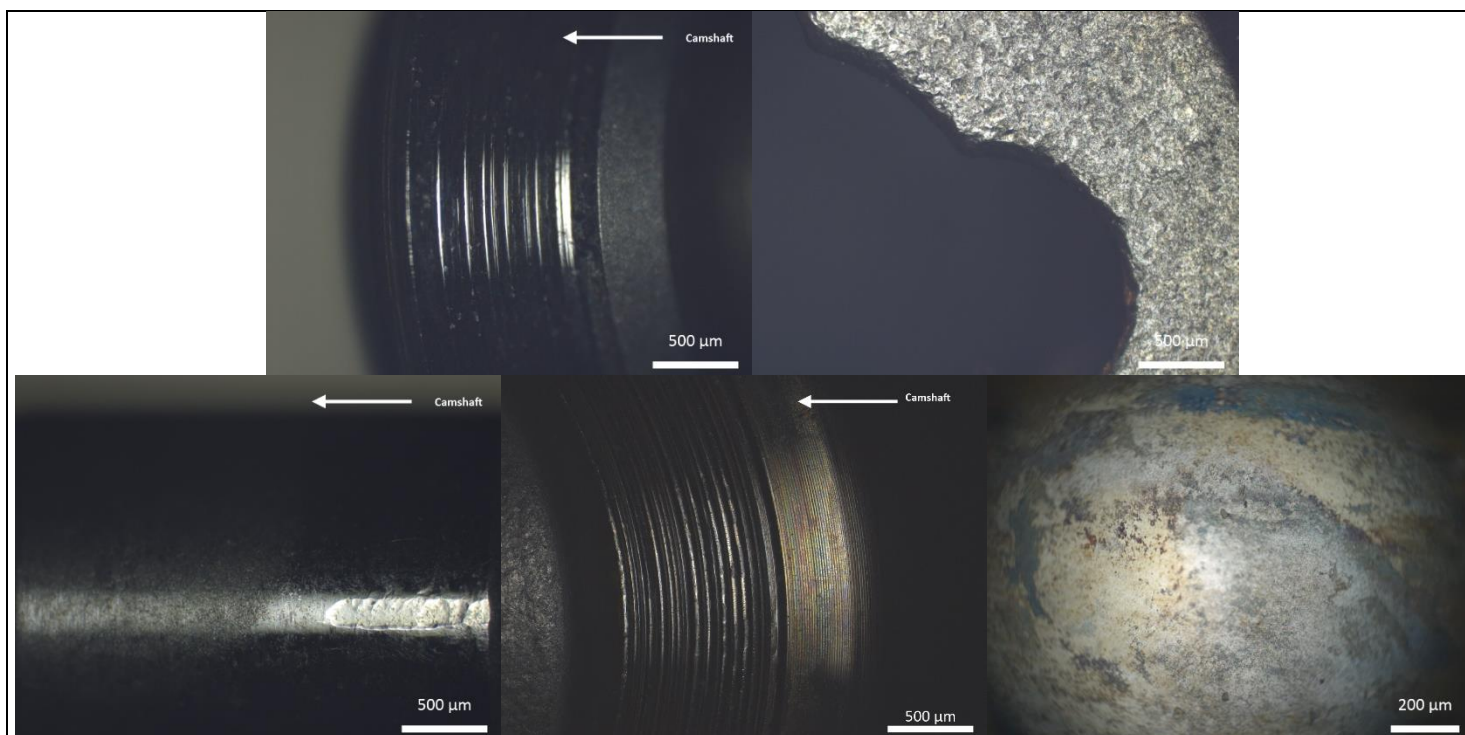


Figure 64. Bright-field optical micrographs of inlet suction and outlet check valves from pump 2 (fuel 1, 1052 h). Bottom left, conical section of inlet suction valve; top left, cylindrical section of inlet valve; bottom center, inside of inlet valve seat; top right, outside of inlet valve seat; bottom right, check valve ball.

3.4.3 Pump 3 (1800 h, Used until Inlet Clogged)

The valves and valve seat from pump 3 had a similar appearance as those from pump 2 except they were significantly more discolored (Figure 65). The discoloration was particularly apparent in the outlet check valve.

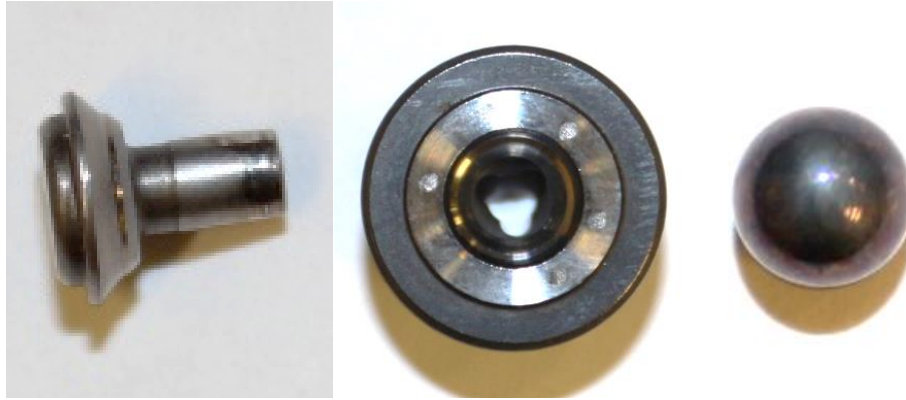


Figure 65. Inlet suction and outlet check valves from pump 3 (fuel 1, 1800 h). Left, inlet suction valve; bottom center, inlet valve seat; right, check valve ball.

Bright-field micrographs of the valves and valve seat show the discoloration and wear in more detail (Figure 66). The inlet valve for pump 3 had patches of brown on the surface as opposed to the valve from pump 2. The inlet valve from pump 3 was smoother towards the tips of the cylindrical portion, similar to what was observed from pump 2. The inside of the inlet valve seat had circumferentially oriented grind marks and had a dark-brown coloration. The brown discoloration was also observed on the outside of the valve seat from pump 3, unlike from pumps 1 and 2. The outlet check valves appeared to be brown and blue. The discoloration in the valves is similar to the discoloration of the bucket and plunger, where a thin surface film may have formed.

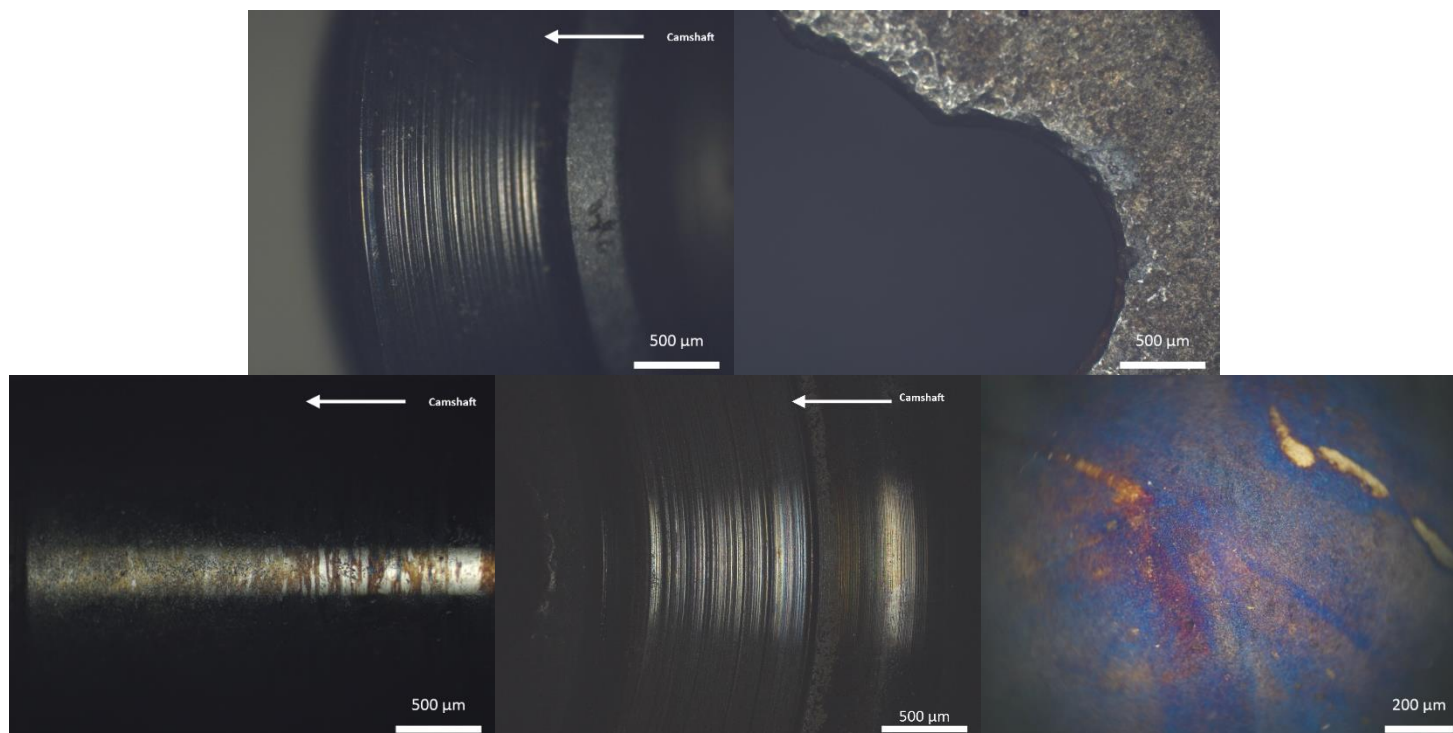


Figure 66. Bright-field optical micrographs of inlet suction and outlet check valves from pump 3 (fuel 1, 1800 h). Bottom left, conical section of inlet suction valve; top left, cylindrical section of inlet valve; bottom center, inside of inlet valve seat; top right, outside of inlet valve seat; bottom right, check valve ball.

3.4.4 Pump 4 (476 h, Failure due to Plunger Seizure)

The inlet valve and valve seat for pump 4 did not have much discoloration, but the outlet valve did have minor discoloration (Figure 67). The inlet valve had a shiny appearance on the tip of the cylindrical section.



Figure 67. Inlet suction and outlet check valves from pump 4 (fuel 2, 476 h). Left, inlet suction valve; bottom center, inlet valve seat; right, check valve ball.

The wear of the pump 4 valves can be seen in the bright-field optical micrographs in Figure 68. The smoothed portion at the tip of the cylindrical portion of the inlet valve is approximately 0.7 mm wide. The conical section has many circumferentially oriented scratch marks similar to the other used pumps. The inside of the inlet valve seat had circumferentially oriented abrasive marks similar to pumps 2 and 3 but did not have significant discoloration. No significant change was observed between the outer surface of the pump 4 inlet valve seat and that of the pristine pump 1. The outlet valve ball can be seen to have some brown discoloration, although significantly less than in pump 3.

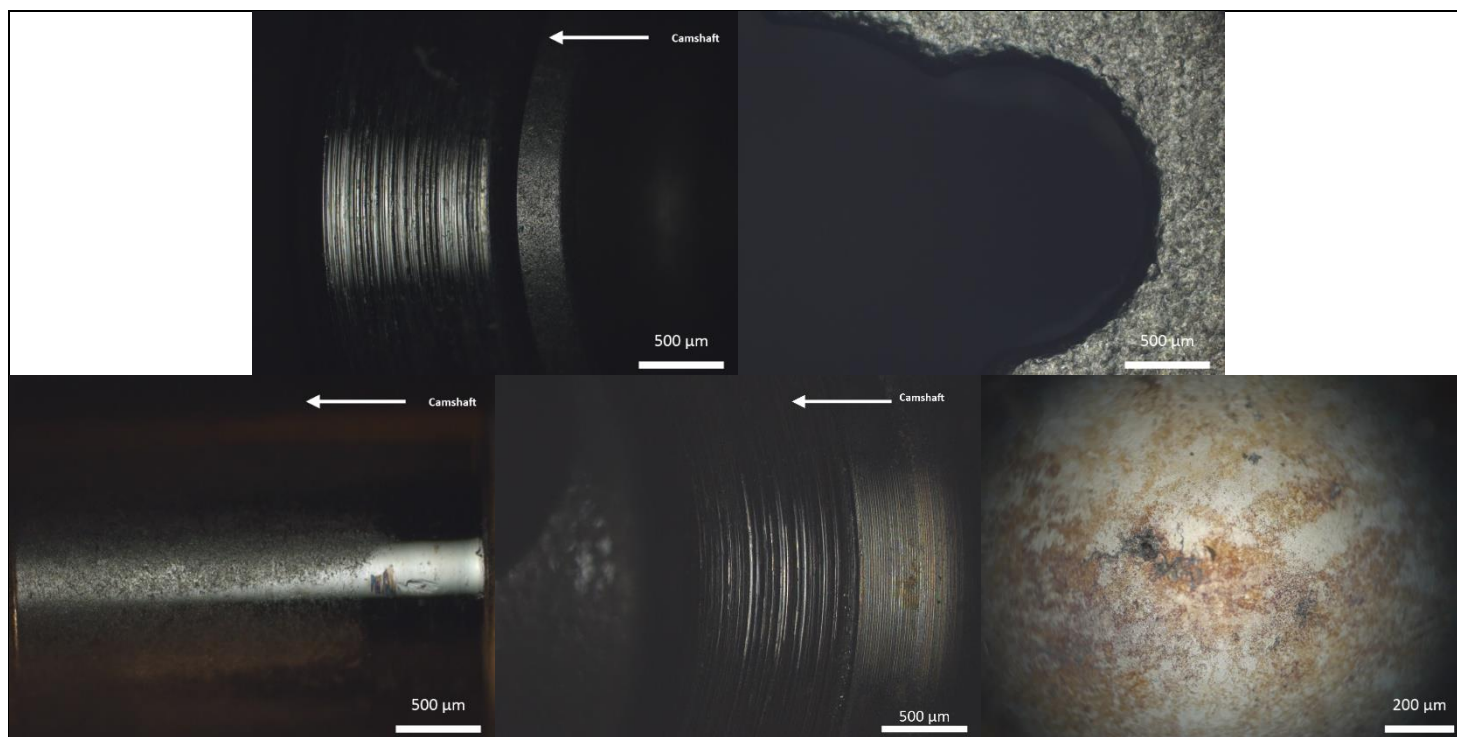


Figure 68. Bright-field optical micrographs of inlet suction and outlet check valves from pump 4 (fuel 2, 476 h). Bottom left, conical section of inlet suction valve; top left, cylindrical section of inlet valve; bottom center, inside of inlet valve seat; top right, outside of inlet valve seat; bottom right, check valve ball.

3.4.5 Pump 5 (1200 h, Failure due to Plunger Seizure)

The valves and valve seat from pump 5 did not have any discoloration, but some wear was visible on the surfaces (Figure 69). The inlet valve had a shiny appearance on the conical portion. The inlet valve seat appeared unchanged. The outlet check valve had a slightly rougher appearance, and there was a ring-shaped depression on the surface.



Figure 69. Inlet suction and outlet check valves from pump 5 (fuel 2, 1200 h). Left, inlet suction valve; bottom center, inlet valve seat; right, check valve ball.

The wear of the valves from pump 5 can be seen in the bright-field optical micrographs in Figure 69. The conical portion of the inlet valve had a scuffed appearance along with many circumferentially oriented abrasive scratch marks. The wear on the conical portion of the pump 5 inlet valve appears to be much greater than the other pumps, however the cylindrical portion appeared to be similar in appearance to the pristine pump. The inside of the inlet valve seat had a scuffed appearance matching the conical section of the inlet valve, to which it mates. The outside of the pump 5 inlet valve seat was similar to the pristine pump except for flatter, shinier asperities. The abrasive scratches on the conical section of the inlet valve were likely caused by abrasion from the large asperities in the valves seat. The inlet valve and the valve seat fit together snugly despite the wear of the surfaces. The outlet check valve surfaces were significantly roughened, with depressions 20–100 μm wide along the entire surface. In addition, the ring-shaped depression observed in Figure 69 appears as a large 100- μm trench in the lower half of the Figure 70 micrograph.

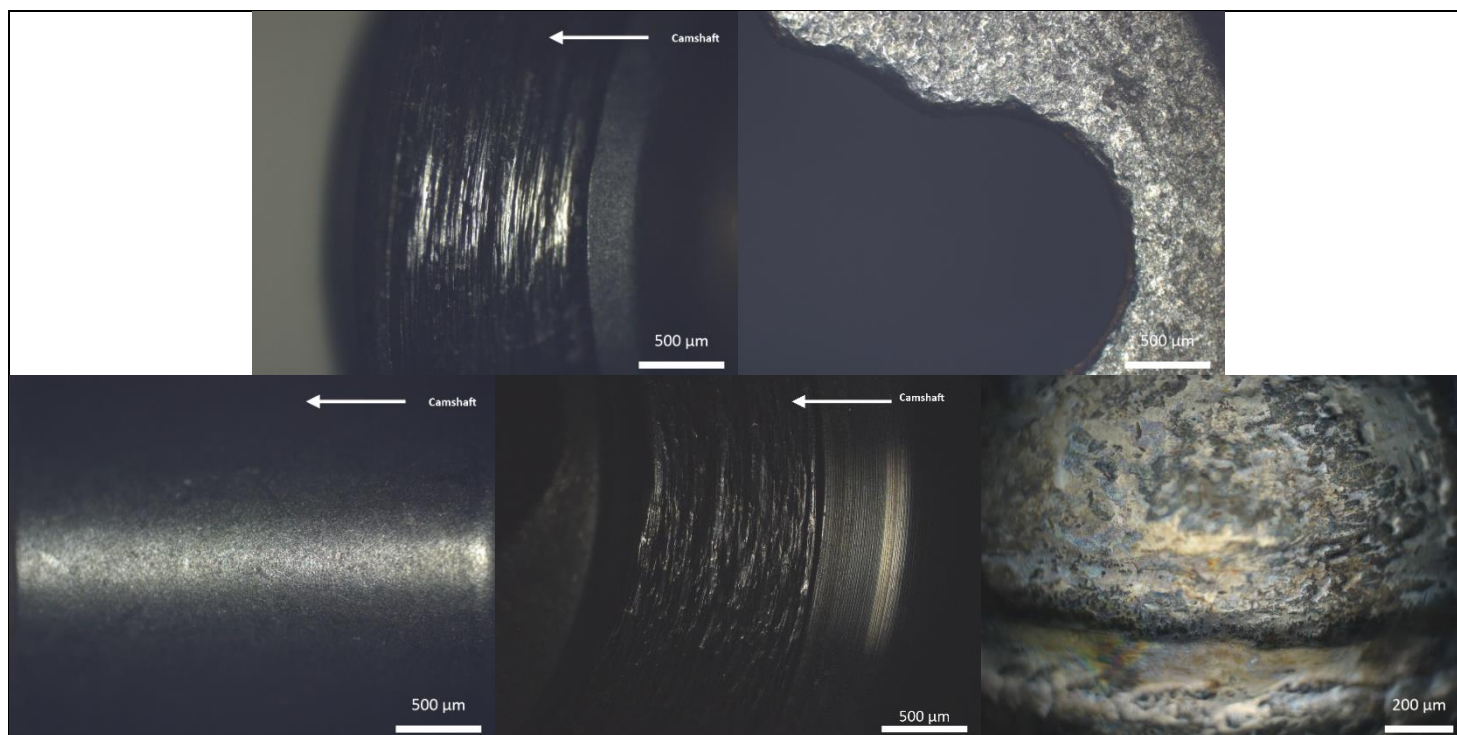


Figure 70. Bright-field optical micrographs of inlet suction and outlet check valves from pump 5 (fuel 2, 1200 h). Bottom left, conical section of inlet suction valve; top left, cylindrical section of inlet valve; bottom center, inside of inlet valve seat; top right, outside of inlet valve seat; bottom right, check valve ball.

4. Conclusions

The analysis of the HPFPs revealed the way the surfaces interact and change during operation and showed how wear was dependent on the fuels that were used during operation. The pumps operated with fuel 1 contained many discolored surfaces, likely due to tempering or chemical interactions with the fuel; however, most surfaces showed low wear. One of these pumps had worn through the diamond-like carbon coating, but the steel surface did not appear severely damaged. In contrast, the pumps operated with fuel 2 exhibited no discoloration but did have several abrasive scratches, likely due to third-body abrasive particles that went past the filter. It was thought these scratches may have resulted in the scuffing of one of the plungers, which resulted in seizure of the plunger and reduction of output flow. Lastly, several observations were made about the pristine pump surfaces. It was discovered that all surfaces in the pumps with a reciprocating motion have a grind perpendicular to the sliding direction except the bucket tappet, which has an isotropic finish. The valves in the pump have an isotropic finish and mostly experience an impact-sliding contact. Most parts were made of a low-alloy chromium containing steel with approximately 60 HRC hardness. The cam ring had additional protection from a diamond-like carbon coating.

5. References

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List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
BOCLE	ball-on-cylinder lubricity evaluator
EDS	energy dispersive spectrometer
HFRR	high-frequency reciprocating rig
HPFP	high-pressure fuel pumps
HRC	Rockwell hardness scale
NA	not applicable
SE	secondary electron
SEM	scanning electron microscope
SLBOCLE	scuffing load ball-on-cylinder lubricity evaluator

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