Multi technical analysis of wear mechanisms in axial piston pumps

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Abstract. Axial piston pumps convert a motor rotation motion into hydraulic or pneumatic power. Their compactness and efficiency of approximately 0.9 make them suitable for actuation applications especially in aeronautics. However, they suffer a limited life due to the wear of their components. In the literature, studies of axial piston pumps deal with contact between its different elements under lubrication conditions. Nevertheless, they are more focused on analytic or numerical approaches. This study consists in an experimental analysis of worn pump components to highlight and understand wear mechanisms. Piston shoes are central components in the axial piston pump since they are involved in three tribological contacts. These three contacts are thereby studied: piston shoes/swashplate, piston shoes/pistons and piston shoes/ shoes hold down plate (SHDP). To perform this analysis, helicopter hydraulic pumps after different operating times have been studied. The wear damage mechanisms and wear debris are analysed using SEM observations. 3D surface roughness measurements are then used to characterize worn surfaces. The observations reveal that in the contact between shoes and swashplate, the main wear mechanism is three-body abrasive wear due to coarse carbides removal. Between shoes and pistons, wear occurs in a less severe way and is mainly due to the debris generated in the first contact and conveyed by the lubricating fluid. In the third contact, the debris are also the prime cause of the abrasive wear and the generation of deep craters in the piston shoes.

1. Introduction
Axial piston pumps convert the mechanical power generated by a motor rotation into hydraulic power. The motor rotational motion is transmitted to a barrel by a shaft. Pistons within the barrel are held on a tilted plate - the swashplate. Consequently, the barrel rotation drives the pistons to translate in their bore and pump the fluid. Then a two-holed plate - the valve plate - distributes the fluid between two conducts (inlet and outlet). The hydraulic fluid also plays a lubricating role since the carter is filled with the fluid. In regular cases, piston shoes (or shoes) are added to improve pistons driving on the swashplate and create a plane on plane contact. To improve lubrication in the contact between shoes and swashplate, a small cavity in each piston/shoe assembly provides pressurized fluid. Shoes are kept in contact with the swashplate by the action of a retainer: here a shoe-hold-down-plate (SHDP) and a spring. The mechanism and kinematics of axial piston pumps are detailed by many authors [1–5].
Figure 1. Axial piston pump exploded view.

The hydraulic fluid flows in the carter and in the circuitry, and thus lubricates all contacts between components. Deeken [6] simulated the combined hydrodynamic and tribological phenomena in valve plate/barrel, pistons/barrel and shoes/swashplate contacts. Some authors combined simulations and measurements for several contacts in an axial piston pump [5, 7, 8]. The lubricating film in shoe/swashplate contact is the most simulated or studied in literature [9–16]. Despite this lubrication of every contact, each component undergoes wear at different levels and by generating wider gaps and greater leakage flows, this loss of material results in declining performances and reduced life. Wear can also lead to catastrophic failure. Consequently, it is necessary to study and understand wear mechanisms in axial piston pump.

Wear is a complex phenomenon and is rarely simulated in axial piston pumps or analogue systems. The above-mentioned simulations and experiments are focused on lubrication film thickness, contact pressures, heat generation, elastic and plastic deformations due to the fluid-structure interactions. These quantities are linked to wear volume but the dependence on wear mechanism is complex to establish. Indeed, laws of wear have been developed to predict wear and correlate experimental results [17–21].

For example, Archard and Holm proposed a simple law of wear [22, 23], but it is initially limited to dry contact and the constant K is not well understood [24]. Stolarski and Zou et al. developed abrasive wear models for lubricated contact for prediction [25, 26].

Ma et al. adapted Zou’s model for the contact between shoes and swashplate [27]. They compared simulations results to experimental wear rate evaluations that consisted in measuring a variation of shoe thickness before and after testing. Wang et al. proposed a statistical approach to predict the remaining useful life of an axial piston pump, and compared result to experiments by monitoring return oil flow (sum of leakage in four contacts) as a consequence of internal wear [28]. Some experimental studies are performed on test machines instead of test rigs with adapted setup to reproduce the pumps contacts [29, 30]. It allows a simpler control of operating conditions but in accordance with pump contact specifics.

Kalin et al. observed the influence on wear resistance of DLC-coated shoes. They followed wear evolution with optical microscope and leakage monitoring [31]. This type of qualitative study can be found on other systems than axial piston pumps. Mucchi et al. determined lubrication regimes in variable displacement vane pumps by measuring roughness to quantify
wear [32]. Archard’s law $K$ takes typical values depending on the lubrication regime and has been identified with the experimental wear volumes. Brandao et al. and Maruda et al. did complete analyses of wear of respectively gears and a cutting tool for different operating conditions [33, 34]. These studies are close to the one conducted in this paper. Indeed, surfaces are analysed after normal use with techniques such as optical microscopy, SEM, X-rays micro analyses or 3D optical topography, and qualitative conclusions are drawn.

This literature review shows that few wear analyses are performed on real components of axial piston pump. More generally, there is a lack of qualitative analyses aiming to understand wear mechanisms. A better knowledge of these mechanisms enables to choose more accurately wear prediction models. From an engineering point of view, it also permits to propose tailored wear resistance improvement solutions for each contact. This study consists in an experimental analysis of worn pump components to highlight and understand wear mechanisms. It is conducted on helicopter hydraulic pumps after different operating times. The wear damage mechanisms and wear debris are analysed using SEM observations. 3D surface roughness measurements are then used to characterize worn surfaces. The study provides information on wear mechanisms and chronology by using a multi-technical analysis.

2. Material and methods

2.1. Material - The pumps

In this paper, the study focuses on helicopter axial piston pumps. Five pumps of the same model have been sampled after different operating times, but similar operating conditions. The components and subsystems are detailed in the introduction but some extra information is required to perform this study:

The swashplate and pistons are made of the same high carbon martensitic stainless steel. The bars that are machined into swashplate and pistons did not receive the same treatment during steelmaking. As specified by the norms AIR 9160 and AIR0819, classes are distinguished by a limit size of inclusions. Class 2 (bigger inclusions) is manufactured in a usual steelmaking furnace. Whereas class 3 is refined in a vacuum furnace after the usual steelmaking furnace. Consequently, class 3 has less impurities and finer carbides. Once the components are machined, they are thermally treated to reach a hardness higher than 58 HRc and a good thermal stability. This treatment is identical for classes 2 and 3. The SHDP is made of nitrided steel and the shoes of a copper alloy.

2.2. Measurement

The aim of this study is to understand wear mechanisms and their evolution during time in the three following contacts: shoes/swashplate, shoes/pistons and shoes/SHDP. For each contact, the contacting surfaces are analysed.

Five pumps are observed and analysed after 0h, 300h, 550h, 870h, and 1050h real operating times. Then, they are disassembled and the concerned components for the different analyses. Scanning electronic microscope (SEM) observations are performed to obtain a first understanding of the microstructure evolution and the wear phenomena that occurred in the different contacts. Chemical analysis completes this approach by giving insight on adhesion phenomena, nature of debris. 3D surface roughness measurements characterize worn surfaces in order to determine abrasive wear mechanisms and areal roughness parameters of the worn surfaces.

2.3. Method for roughness analysis

Roughness enlightens wear chronology and severity compared to the initial state. However, a good choice of parameters is mandatory. The arithmetic mean deviation of the surface (Sa) will be studied, because it provides a first general information on the surface roughness. However,
Sa alone is not enough because several surfaces with a similar Sa can have totally different topologies. Hence the need for more functional parameters [35, 36]. Various authors use Abbott-Firestone bearing curves and their derived parameters to monitor wear [37–42]. The Abbott-Firestone curve is the cumulative density function of surface heights.

![Abbott-Firestone curve and derived parameters](image)

**Figure 2.** Abbott-Firestone curve and derived parameters from [37], adaptated for surfaces.

As a complement to Sa, the five parameters on the Abbott-Firestone curve (fig 2) will be studied (ISO 13565-2):

- Spk: reduced summit height
- Svk: reduced valley depth
- Sk: core roughness depth
- SMr1: Percentage of surface considered as peaks
- SMr2: Percentage of surface considered higher than valleys

To make SMr2 easier to compare to SMr1, its complementary to 100, SMr2 = 100-SMr2, will be used instead.

All these roughness parameters are given in a normalized form. Parameters in micrometers (Sa, Sk, Spk, Svk) are normalized with respect to Sa. SMr1 and SMr2’ (in %) are normalized with respect to SMr1.

### 3. Results and discussion

The results of the analysis are detailed below. First, a table with the measured Vickers hardness is presented.

| Material            | Pump components                  | Vickers Hardness (Hv5) |
|---------------------|----------------------------------|------------------------|
| Stainless steel     | Swashplate, pistons              | 903.3 ± 42.7           |
| Copper alloy        | Shoes                            | 249.8 ± 1.2            |
| Nitrided steel      | Shoes hold down plate            | 1159.5 ± 58.4          |

**Table 1.** Measured Hv5 hardness of the different materials.
### 3.1. Swashplate - Shoes contact

The shoes are made of a copper alloy and the swashplate of a thermally treated stainless steel. This treatment results in a martensitic matrix sprinkled with fine and coarse chromium carbides. The pistons-shoes assembly is designed to ensure lubrication in the swashplate-shoes contact. However, this contact is open, which enables the lubricant to flow out of it. Accordingly, a higher stress concentration occurs on the shoes border. The following results show how this configuration influence wear mechanisms.

The SEM observations of the swashplates surfaces (figure 3 A) show a combination of motor-rotation-oriented and randomly oriented grooves of approximately 5 micrometers large. This highlights two-body and three-body abrasive wear. The same conclusions can be drawn from the SEM observations of the shoes surfaces (figure 3 B) with larger (until 15 micrometers), more randomly oriented and more numerous grooves.

The presence of copper smearing on the swashplate cannot be confirmed by EDX, because of the too small thickness of the deposit. Therefore, hypothesis are made after optical microscopy. A copper-colored deposit is observed on the swashplate (figure 4). This confirms the soft adhesive wear, and the limit lubrication regime.

The EDX analysis reveals the third-body is composed of chromium carbides (figure 5 left). These carbides are removed from the swashplate stainless steel surface (figure 5 right) and generate grooves on the contacting surfaces. They also get stuck in shoes surfaces (figure 5 left) and scratch the swashplate.

**Figure 3.** SEM pictures: A) Swashplate, B) Shoe in contact with the swashplate after 0h and 1050h functioning time. Generation of grooves.
Figure 4. Copper smearing on the swashplate after 1050h functioning hours.

Figure 5. SEM pictures with EDX pointing on chromium carbides. (left) chromium carbide stuck in a shoe surface, (right) swashplate surface with removed carbides.

These removed carbides seem to be the coarse carbides as shown in the following microstructure (figure 6). According to various authors they are undissolved M7C3 eutectic carbides [43–47]. This explains the presence of a carbide composed third-body. The other component of the third-body is a mix of strain hardened debris from the different parts of the pump.

Between 0 and 300 hours (figure 7), the swashplate is worn by running-in (Sa and Sk decrease). Peaks that are higher than the bearing surface are more numerous and conserv their height whereas valley that are lower than the bearing surface. It can be explained by important losses under the mean line, such as carbides removal and grooves (three-body abrasive
wear). Meanwhile, the whole shoes surfaces are more severely worn. The small variation of SMr parameters means an almost constant quantity of high peaks and deep valleys. However, peaks and valleys that are not wide enough to be counted as peaks and valleys increased, hence a higher Sk. This variation corresponds to a three-body abrasive wear mechanism. Between 300 and 870 hours, the same mechanisms occur on the swashplate but with less intensity. Less carbides are removed and a two-body abrasive wear begins. In the meantime, a third-body randomly pollutes the fluid and generate random grooves. The shoes also experiment theses combined mechanism, but the rise of Svk and MMr2 displays the generation of more grooves. During the last period, shoes surface seem to be more polished but with more peaks eventough their height decreases. Carbides and particles getting stuck in shoes surfaces explain this result and the increase in swashplate parameters; the particles that are stuck in the shoes scratch the swashplate.

While studying failure and cracks in blades made of 440C, Neri and Colas, concluded that the failure was due to the presence of brittle coarse carbides [48]. Indeed, they initiated crack or provided easy crack path. The brittleness of coarse carbides might explains their removal from the martensitic matrix. Meurling et al found the same result for several steel grades [49].
Carbide have a direct influence on matrix as well. Indeed, coarse carbides are due to a non-optimal austenizing temperature and can result in a lower carbon concentration in the matrix and a lower strength [47]. The following sections show that the impact of this carbide removal is not limited to this contact.

3.2. Pistons - Shoes contact
The cyclic motions of the pistons in the shoes bring the lubricant in the contact. Since this ball-joint is a semi-closed contact the fluid is then trapped in it. Hence, the high stress concentration due to sphere-on-sphere contact is avoided by the constant presence of lubricant. The absence of copper (optical microscopy) on the piston sphere tends to confirm the effective lubrication in the ball-joint.Besides external particles and debris pollution are partially blocked by this semi-closed contact.

The SEM observations of the pistons surfaces (figure 8 A)) show rare grooves and no carbides removal. The shoes’ initial machining grooves seems to have been polished and replaced by randomly oriented grooves (figure 8 B)). This mechanism is a combination of two and three-body abrasive wear.

![SEM pictures: A) Piston, B) Shoe after 0h and 1050h functioning time.](image)

Figure 8. SEM pictures: A) Piston, B) Shoe after 0h and 1050h functioning time.

The microographies show no carbides removal from the piston surface. It is indeed prevented by the lubrication conditions. In addition, less coarse carbides lines are observed in pistons microstructure (figure 9), hence less carbides can be removed. This confirms the effect of secondary steelmaking made on the class 3 high carbon martensitic stainless steel.
The small probability of carbide removal in pistons is also due to their machining process. Swashplate and pistons are machined from steel bars. The coarse carbides lines are in the same direction as the bars. Consequently, there are more coarse carbides in contact with shoes on the swashplate than on the piston sphere.

However, there are random grooves due to a third-body in the shoes surfaces (figure 10). This contact is thus polluted by debris and carbides coming from other contacts, especially between swashplate and shoes.

According to the roughness parameters analysis (figure 11), the piston sphere is slightly polished until the appearance of grooves between 870 and 1050 hours of functioning. The shoes spheres are polished too, but also suffer a three-body abrasive wear due to polluting particles (Spk variations and SvK decrease with constant SMr). Between 870h and 1050h, new grooves are generated and new particles are stuck in the surface and will scratch pistons’ spheres.

3.3. SHDP - Shoes contact

When the edge of shoes enter in contact with the SHDP, a stress concentration occurs. The SHDP is made of nitrided steel and has a hardness of Hv5 1159.5±58.4 against Hv5 249.8±1.2 for the copper alloy shoes (table 1). The surface of SHDP in contact with the shoes seems to be lightly polished (figure 12 A)), whereas the shoes seem serverely worn (figure 12 B)). The surface is impacted and worn by two-body abrasion. Although, wear is not regular on the whole surface and some zones with the initial machining grooves can still be observed.
Figure 11. Evolution of different normalized roughness parameters for pistons-shoes contact.

Figure 12. SEM pictures: A) SHDP, B) Shoe after 0h and 1050h functioning time.

Observation of sliced SHDPs (figure 13) confirms that wear is limited on their surfaces. The nitriding combination layer (1 to 2 micrometers thick) resisted 1050 functioning hours.

EDX analysis of the impacts on the shoes surfaces explain their origin. Carbides and debris that pollute the fluid are trapped between the surfaces and pressed in the shoes because of the hardness difference between SHDP and shoes (figure 14 left). It generates edge formations and a remaining crater (figure 14).
In addition, the edges of the shoes enter in contact with the SHDP, the load is concentrated and a plastic deformation occurs (figure 15).

Due to these combined wear mechanisms this surface of the shoes is reported to be the most worn surface of the pump. The decrease of roughness parameters on the SHDP reflects a polishing without other signs of wear (no groove or impact): running-in (0 to 550h) and soft abrasive wear. On the shoes, between 0 and 550h, particles and debris are getting stuck in the surface (less valleys, more peaks, both wider). After 550h, the particles seem to have left the shoes with deep valleys (grooves and craters) that are progressively removed by two-body abrasive wear (figure 16).
Figure 16. Evolution of different normalized roughness parameters for SHDP-shoes contact.

The fluid pollution with carbides and other particles is a form of fluid contamination. In their overview about fluid contamination in hydraulic systems, Frith and Scott concluded that an appropriate filtration is compulsory to limit contamination effects. However, they inferred that improving wear resistance of component is also necessary [50]. It is in accordance with the quasi no wear of the SHDP surface opposed to the important wear of shoes which are made of the softest material in the assembly. Kalin’s study of DLC-coated shoes on a laboratory hydraulic system displays similar conclusions: shoes surfaces with only two-body abrasive wear in the rotation direction [31]. The DLC coating increased shoes’ hardness and resistance to third-body. He also reported less wear debris generation.

4. Conclusions
Wear mechanisms in axial piston pumps have been investigated using a multitechnical analysis. The conditions of contact are different for the three tribological contacts and influence the severity of wear.

• The swashplate is a thermally treated stainless steel with a martensitic matrix and a combination of fine and coarse chromium carbides. As a consequence of the uncertain lubrication and the stress concentration on shoes borders, carbides are removed from the matrix and act as a third body. This ensuing important abrasive wear of both the surfaces is typical of dry friction or boundary lubrication cases. The removed carbides pollute the fluid and the and the other two contacts.

• The pistons’ stainless steel is the same as the swashplate’s with rarer coarse carbides. This contact is a ball joint which traps the fluid and offers a better lubrication. It also limits the intrusion of external particles and debris. These combined effects of the ball-joint result in a less severe wear of the antagonist surfaces. Indeed, the wear of the piston surface is very low. Additionally, the lower quantity and size of coarse carbides also prevents carbides removal from the piston. However, deep grooves and holes due to carbides are observed on the shoes. The three-body abrasive wear is thus mainly due to external particles. Carbides are removed in the first contact and conveyed by the fluid.

• The SHDP is made of a nitrided martensitic steel. The contact with shoes is open and immersed in the carter-pressurized fluid. Lubricant can be exhausted from the contact, which lead to a limited lubrication. When the edges of shoes enter in contact with the SHDP, the stress concentration results in plastic deformation. Debris and carbides get stuck
between the two surfaces, are pressed in the shoes surface, which generates edge formations and craters. These deformations are then gradually removed by two body abrasive wear. In regard of the 3 different contacts, the shoes in this contact are the most worn surfaces, whereas the SHDP is just slightly polished.

In the three studied contacts, wear is due to carbide removal and to the comparatively low shoes’ hardness.

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