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Tribological Mechanisms in Water Hydraulic Axial Piston Pumps: Insights into Lubrication, Cavitation, and Wear Control

Assoc. Prof. PhD. Eng. **Ștefan ŢĂLU**[1,*]

[1] Technical University of Cluj-Napoca, The Directorate of Research, Development and Innovation Management (DMCDI), Constantin Daicoviciu Street, no. 15, Cluj-Napoca, 400020, Cluj county, Romania

* stefan_ta@yahoo.com

Abstract: *Water hydraulic axial piston pumps (WHAPs) represent a critical innovation in eco-sustainable fluid power systems, yet their tribological behavior under water-lubricated conditions remains a persistent engineering challenge. This study provides a focused review of three key tribological mechanisms - hydrodynamic effect, cavitation effect, and wear debris storage - essential to understanding and optimizing the performance of friction pairs in such pumps. Under hydrodynamic and mixed lubrication regimes, surface textures induce convergent and divergent geometries that generate localized pressure build-up, enhancing load-carrying capacity and fluid film stability. Concurrently, cavitation effects induced at the trailing edges of micro-features serve to mitigate negative pressures, stabilizing the lubrication environment. In the absence of sufficient lubrication, wear debris storage becomes the predominant mechanism, wherein textured concavities act as micro-reservoirs for entrapped particles, reducing abrasive wear and preserving surface integrity. These mechanisms are critically analyzed in the context of advanced surface engineering strategies, with implications for improving wear resistance and operational reliability. The synthesis of these tribological phenomena underscores the multifaceted advantages of engineered surface textures in mitigating wear and enhancing the operational lifespan of WHAPs. Future research directions are proposed, emphasizing the integration of multi-scale texturing strategies, coupled with coating technologies, under multiphysics environments to further extend the functional reliability of these critical hydraulic components.*

Keywords: *Cavitation, hydrodynamic effect, surface texture, tribological mechanisms, water hydraulic axial piston pump, wear debris storage*

1. Introduction

Hydraulic systems play a key role in industrial operations, and their performance can be effectively analyzed through modeling and simulation [1, 2]. At the core of these systems, hydraulic pumps transform mechanical energy into hydraulic force, enabling the delivery of pressurized fluid for various tasks [3, 4]. With ongoing technological progress, hydraulic pumps are becoming more precise and structurally complex, highlighting the growing demand for reliable, accurate, and intelligent diagnostic methods to detect faults efficiently [5, 6].

The global demand for sustainable, non-polluting, and intrinsically safe technologies has revitalized interest in water hydraulics as a viable alternative to conventional mineral oil-based hydraulic systems [7, 8]. Unlike petroleum-derived fluids, water is naturally abundant, non-flammable, non-toxic, and environmentally benign, offering intrinsic advantages in applications where safety, hygiene, and ecological compatibility are paramount. These include sectors such as food processing, pharmaceuticals, fire suppression, marine engineering, and operations in explosive or high temperature environments where oil-based systems pose severe operational risks [9-12]. Modern hydraulic system development prioritizes high pressure, speed, flow, intelligent control, and system integration, posing significant challenges for pump innovation.

Historically, water was the original working medium in early hydraulic systems, with its usage dating back to the late 18th century [7]. However, the emergence of the petroleum industry and advances in elastomer sealing materials during the 20th century led to the widespread substitution of water by mineral oil, primarily due to the latter's superior lubricity, corrosion resistance, and pressure-handling capabilities. Despite these advantages, mineral oils present significant drawbacks - chiefly their flammability, environmental impact, and incompatibility with sensitive or hazardous environments - limitations that are increasingly unacceptable in modern engineering contexts governed by stringent environmental and safety standards.

Renewed attention to water as a hydraulic medium is therefore both timely and necessary. Nevertheless, water’s inherent physicochemical properties - including low viscosity, high vapor pressure, poor lubricity, and corrosiveness - pose formidable challenges to its application in high-performance hydraulic systems. These challenges are especially pronounced in precision components such as water hydraulic axial piston pumps (WHAPs). The operational reliability, efficiency, and service life of such pumps are strongly influenced by their tribological behavior under water-lubricated conditions, where conventional oil-based design paradigms often fail [13-15].
Key friction interfaces within WHAPs are exposed to severe wear, fluid film instability, and cavitation, especially under extreme loads or high-speed conditions.
The internal structure of WHAPs is highly complex. Recent advancements in materials science - particularly in corrosion-resistant alloys, engineering ceramics, and polymers - have partially addressed these limitations. However, a complementary and increasingly promising solution lies in the domain of surface texture engineering. Surface texturing introduces micro- and nanoscale geometries that actively modulate lubrication regimes, support hydrodynamic pressure generation, mitigate cavitation, and trap wear particles, thereby enhancing the tribological performance of friction pairs operating in water environments [7, 13-15]. Improving the friction performance of critical contact surfaces in WHAPs largely depends on selecting appropriate material combinations. Research has identified advanced alloys, high-performance plastics, and technical ceramics as durable, corrosion-resistant, and self-lubricating materials suitable for friction components [16–18].
This review provides an in-depth examination of the fundamental tribological mechanisms active in WHAPs, focusing on three interrelated phenomena: the hydrodynamic effect, cavitation effect, and wear debris storage. By elucidating these mechanisms within the framework of surface texture design and advanced tribology, this study aims to contribute to the foundational understanding and practical advancement of water-lubricated hydraulic systems under environmentally responsible and performance-critical conditions.

2. Research methodology

A WHAP is a positive displacement pump commonly used in water-based hydraulic systems. It consists of several main components, including a swash plate, pistons, slippers, a cylinder block, a port plate, and a drive shaft. Axial piston pumps feature pistons arranged parallel to the drive shaft and are typically designed in two configurations: the swashplate type and the bent-axis type.
The structure of the water hydraulic axial piston pump is shown in Fig. 1.

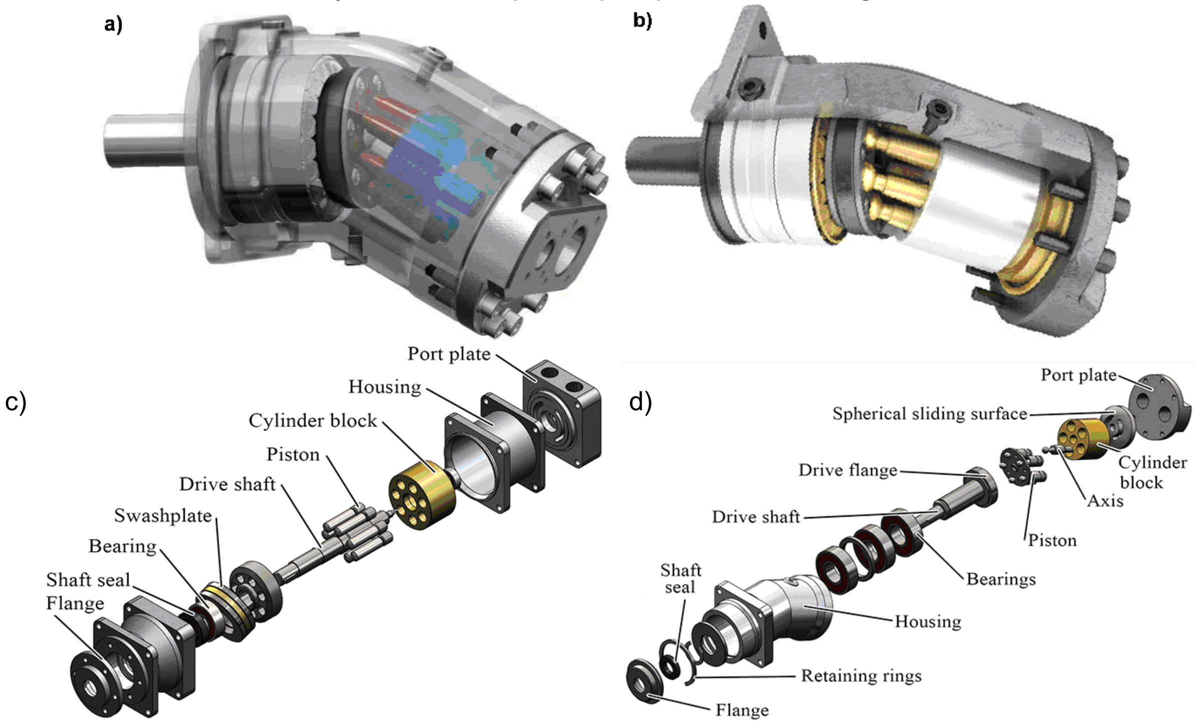

Fig. 1. a,b) axial piston pumps, b) axial piston pump - swash plate type, c) axial piston pump – bent axis type

The swash plate and port plate are fixed in place, while the drive shaft rotates the cylinder block and pistons together. As the cylinder block turns, the pistons slide back and forth within their bores due to the inclined angle of the swash plate, with the slippers maintaining contact with its surface. During one half of the rotation, the pistons move outward from the cylinder block, increasing the volume in the piston chamber and creating a vacuum that draws water into the chamber through the suction port in the port plate. In the other half of the rotation, the pistons are pushed back into the cylinder block, reducing the chamber volume and forcing the water out through the discharge port. This continuous reciprocating motion of the pistons generates a steady flow of pressurized water. Because water has poor lubrication properties compared to oil, the pump is designed with tight clearance between the piston and cylinder wall to minimize leakage and improve efficiency. The nature of water hydraulics also means that the pump materials can be less wear-resistant than those used in oil systems. This simplicity in design and operation, combined with the environmental benefits of using water as the working fluid, makes the axial piston pump a preferred choice in water hydraulic applications. In the context of water hydraulic systems, axial piston pumps play a critical role, with the selection of pump type contingent on specific operational demands such as pressure levels, required flow rates, and spatial constraints.
A survey was conducted on lubrication, cavitation, and wear control for WHAPs in the scientific literature from 2000 to 2025.

3. Material strategies for water-lubricated tribological interfaces

This section explores the tribological performance of key material classes - corrosion-resistant alloys, engineering polymers, and advanced ceramics - highlighting how their intrinsic properties and surface interactions determine their suitability for use in water-lubricated environments.

3.1 Advanced corrosion-resistant alloys for water-lubricated applications

In tribological systems operating under water-based lubrication - particularly in seawater - the selection of appropriate metallic materials is crucial due to the synergistic interactions between lubrication, cooling, and corrosion. Conventional alloys often exhibit accelerated degradation in these environments, necessitating the deployment of advanced corrosion-resistant alloys with tailored mechanical and chemical properties. High-performance alloys such as stainless steels (austenitic, ferritic, and duplex), titanium alloys, nickel-based superalloys, and select aluminum alloys have demonstrated enhanced compatibility with water and seawater environments. Their resistance to both chemical attack and mechanical deterioration makes them suitable candidates for the dynamic conditions experienced in water hydraulic axial piston pumps.
A comparative evaluation of metallic materials is shown in Table 1.

Table 1: Comparative evaluation of advanced metallic materials in water-lubricated environments

Material system	Dominant wear mechanism	Friction coefficient (seawater)	Corrosion resistance	Application suitability
304 stainless steel	Abrasive + corrosion wear	0.38–0.42	Moderate	Limited under high stress
316L stainless steel	Mild abrasive + oxide wear	0.24–0.30	High	Pumps, valves, sliding parts
2205 duplex steel	Passivation + low abrasive	0.22–0.26	Very high	Harsh saline environments
Ti6Al4V (TC4)	Fatigue + abrasive wear	0.20–0.25	Very high	Marine pump pistons
Monel K500	Abrasive + corrosive fatigue	0.26–0.30	Excellent	Seawater hydraulics
Aluminum 2024	Predominantly mechanical wear	0.45–0.50	Poor	Not suitable without coatings

For example, alloy pairs such as Cu-6Sn-6Zn-3Pb/AISI321 stainless steel [19], ZChSnSb8-8/52100 steel [20], and advanced combinations like TC4/316L [21], Hastelloy C-276/316L, and

Monel K500/316L [22, 23], undergo a transition from dominant abrasive and plastic deformation wear in dry conditions to combined corrosion-assisted wear in seawater.
Austenitic stainless steels (e.g., 304 and 316L) are widely used due to their excellent corrosion resistance and good formability. However, friction-induced phase transformations, such as the formation of α′-martensite from 304 stainless steel, can enhance hardness while simultaneously triggering galvanic interactions that accelerate surface degradation [24]. Titanium alloys (e.g., TC4, Ti6Al4V) [25, 26] form a stable oxide layer that reduces friction and enhances corrosion resistance, while TC11/GCr15 [27], despite showing reduced friction in seawater, experiences higher material loss due to corrosion-induced fatigue cracking.
Table 2 proposes a conceptual materials performance map to guide alloy selection for water-lubricated components in axial piston pumps.

Table 2: Suggested material selection matrix for water hydraulic applications

Environment type	Load condition	Recommended alloy	Key benefit	Limitation
Fresh water	Low–moderate	316L Stainless Steel	Cost-effective, widely used	Moderate mechanical wear
Seawater	Moderate–high	Duplex 2205	High chloride resistance	More expensive fabrication
Seawater + stress	High	Ti6Al4V (TC4)	Passive film, low density	Fatigue-sensitive
Acidic media	Any	Hastelloy C-276	Outstanding chemical stability	Cost, availability
Mixed conditions	Moderate	Monel K500	Balanced corrosion/mechanical	Precipitate aging effects

3.2 Advanced engineering polymers in aqueous tribosystems

Engineering polymers represent a pivotal material class for tribological interfaces in water-lubricated environments due to their inherent resilience, conformability, and ability to entrap abrasive particles, mitigating third-body wear. Unlike metals, these thermoplastic composites exhibit viscoelastic behavior and recoverability under cyclic loading, making them attractive for dynamic sealing and sliding applications in axial piston pumps.
Table 3 shows a comparative overview of modern engineering polymers, outlining key performance attributes, failure mechanisms, and enhancement strategies in aqueous tribological regimes.

Table 3: Comparative performance of engineering polymers in water-lubricated tribological systems

Material	Lubrication behavior in water	Dominant degradation mode	Functional groups or fillers	Suggested rein-forcement strategy
PTFE	Low friction due to boundary water films; poor adhesion of transfer films	High wear under load; no effective film on counterface	Inert; often filled with MoS_2 or graphite	Fiber + particle hybrid filling (e.g., CF + ceramic)
PEEK	Adsorption of water via carbonyls forms lubricating layer; water cools and plasticizes interface	Swelling-induced softening; crack propagation	Carbonyl-rich backbone	Short fiber (CF, GF) reinforcement; nano-ceramics
PI	Hydrogen bonding enables hydration film; water lowers modulus and friction	Hydrolysis and fatigue crack formation	Imide and amide groups	Solid lubricant (e.g., graphite, MoS_2) inclusion
PA (Nylon)	Strong water absorption limits film formation; hydrolysis at elevated friction	Surface erosion and embrittlement	Amide linkages	Mineral fillers to inhibit hydrolysis
PPS	Stable in water; maintains structure; minor swelling	Slight surface weakening; sublayer delamination	Sulfide bridges; aromatic rings	CF + nano-SiO_2 to enhance stiffness
UHMWPE	Low water absorption; good self-lubrication; forms thin hydration film	Poor abrasive resistance due to low hardness	Linear polyethylene chain	Nano-fillers and surface texturing

Prominent examples include polytetrafluoroethylene (PTFE), polyether ether ketone (PEEK), polyimide (PI), polyamide (PA), polyphenylene sulfide (PPS), and ultra-high molecular weight polyethylene (UHMWPE). These polymers exhibit unique water-lubrication behaviors that involve film formation, hydrogen bonding, and water-assisted thermal softening. However, the relatively low mechanical strength and abrasive resistance of base polymers necessitate functionalization through micro/nanoscale reinforcements such as fibers (e.g., carbon or glass) or solid lubricants (e.g., graphite, MoS_2, ceramic particulates) [28-32].

3.3 Advanced ceramics for water-lubricated interfaces

Advanced ceramic materials offer outstanding mechanical stiffness, compressive strength, and chemical inertness, positioning them as high-performance options for water-lubricated tribological interfaces. These materials - such as silicon nitride (Si_3N_4), silicon carbide (SiC), and MAX-phase ceramics like Ti_3AlC_2 - are known for their extreme hardness, reduced density, and thermal stability. However, their intrinsic brittleness and inability to embed or conform to surface asperities can intensify third-body abrasion under harsh sliding conditions. In aqueous or saline environments, a distinct tribochemical process occurs at the ceramic interface. Hydrolysis and ionic exchange reactions between the ceramic surfaces and water molecules or seawater ions promote the in situ generation of hydrated surface films. These tribofilms, typically rich in hydroxides or amorphous silica-like compounds, act as a protective boundary that diminishes friction and wear. Moreover, seawater's ionic species - such as Na^+ and Cl^- - can catalyze these reactions, enhancing film growth and mechanical stability. This enables the transition from dry boundary lubrication toward more favorable mixed or even hydrodynamic lubrication regimes.
Table 4 shows functional tribological assessment of engineering ceramics in aqueous lubrication.

Table 4: Functional tribological assessment of engineering ceramics in aqueous lubrication

Material pair	Water-based medium	Friction dampening behavior	Surface fatigue resistance	Application suitability
Si_3N_4 / Si_3N_4	Deionized water	Progressive under thermal load	High	Precision valves, microbearings
SiC / Si_3N_4	Simulated seawater	Rapid under high ion content	Moderate	Marine bearings, shaft seals
Al_2O_3 / Al_2O_3	Freshwater	Limited improvement	Low	Low-load wear interfaces
Ti_3AlC_2 / SiC	Seawater (high salinity)	Immediate under contact stress	High	Subsea actuators, piston skirts
SiC / Al_2O_3	Brackish water	Delayed under cyclic load	Moderate	Desalination equipment

4. Tribological mechanisms

WHAPs operate under unique tribological conditions due to water's low viscosity, high polarity, and incompressibility. The fundamental mechanisms governing their tribological performance involve complex interactions between surface texture, fluid dynamics, and material properties. These mechanisms primarily encompass hydrodynamic effects, cavitation phenomena, secondary lubrication effects, and wear debris storage.

4.1 Lubrication regimes and the Stribeck curve

The Stribeck curve characterizes the relationship between the coefficient of friction and the Hersey number, delineating three primary lubrication regimes: boundary, mixed, and hydrodynamic lubrication (fig. 2) [32]. In boundary lubrication, direct asperity contact dominates, leading to higher friction. As the speed or viscosity increases, a transition to mixed lubrication occurs, where partial fluid films begin to separate the surfaces. Further increases lead to hydrodynamic lubrication, characterized by a full fluid film that minimizes friction and wear.
Hersey number can be expressed as the following formula [33]:

$$Hersey\ \ number = \eta \cdot N / P \tag{1}$$

where: η is the dynamic viscosity of the lubricant, N is the entrainment speed of the lubricant, P is the applied load.

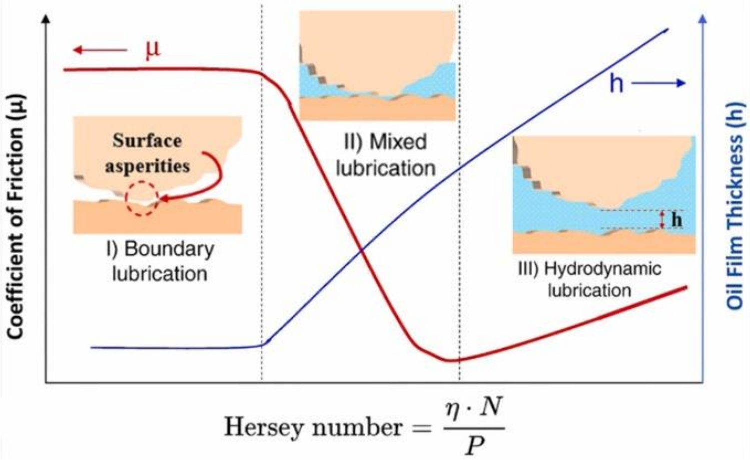

Fig. 2. A typical Stribeck curve illustrating the transition between lubrication regimes. (Reprinted from ref. [33] with permission of Elsevier Ltd. Publisher).

4.2 Lubricant film dynamics and cavitation mitigation

Cavitation is a critical multiphase flow phenomenon encountered in hydraulic systems, characterized by the nucleation of vapor cavities within a liquid when local pressures fall below the fluid's saturation vapor pressure. These vapor bubbles, once formed, are transported into regions of higher pressure where they undergo violent collapse, producing intense localized pressure pulses. This collapse not only induces substantial surface erosion and structural fatigue, but also disrupts fluid flow, leading to elevated noise levels, vibration, and instability. In long-term operation, cavitation can severely compromise the functional integrity of hydraulic components such as pumps, diminishing efficiency, accelerating wear, and escalating maintenance demands [34]. While the fundamental physics of cavitation has been extensively explored, most existing studies emphasize macro-scale groove geometries and overlook the nuanced role of surface microtextures - particularly hemispherical patterns - in modulating cavitation behavior at the microscale [6]. A deeper understanding of texture-induced cavitation mechanisms remains essential for the advancement of high-performance, water-lubricated hydraulic systems [35].

Surface texturing plays a significant role in enhancing the hydrodynamic effect and controlling cavitation in water-lubricated systems. Micro-irregularities on the surface create convergent and divergent wedges in the lubricant film, leading to enhanced pressure generation in the convergent zone and cavitation suppression in the divergent zone. This results in improved bearing capacity of the lubricant film, preventing direct contact between moving surfaces and reducing wear.

According to Hamilton [36], the asymmetric pressure distribution between the leading and trailing edges of micro-structured surfaces reduces negative pressures, preventing film rupture and minimizing cavitation risks. In hydrodynamic and mixed lubrication regimes, surface textures can significantly influence lubrication performance, depending on their geometry, depth-to-diameter ratio, and arrangement. Studies have shown that the shape, area ratio, and contact mode (line or surface contact) of the surface texture can further modulate the performance, enhancing film formation and cavitation control. While cavitation has been widely studied in hydromechanics, existing literature primarily emphasizes groove-induced cavitation and its macroscopic characteristics.

Junyu et al. [37] visualized microscale cavitation induced by hemispherical textures, revealing pressure–phase change dynamics in vapor–oil systems and proposed a simplified friction pair multiphase model. During cavitating flow, dynamic interactions occur between the liquid and vapor phases, involving the continuous transfer of mass and volume fractions. This interphase exchange is governed by transport equations that describe the evolution of vapor volume within the fluid domain [37]:

$$\frac{\partial(\lambda_v \rho_v)}{\partial t} + \nabla(\lambda_v \rho_v u) = \overset{*}{m} \tag{2}$$

where: λ_v is the volume fraction of the gas phase, ρ_v is the gas density of the gas phase [kg/m^3], u is the vector velocity of the gas phase [m/s], and $\dot{m}$ is the source term for evaporation and condensation.

The rates of variation in bubble volume and mass are calculated by the following expressions [37]:

$$\frac{dV_B}{dt} = \frac{d}{dt}\left(\frac{4\pi}{3}R_B^3\right) = 4\pi R_B^2\sqrt{\frac{2}{3}\frac{p_v - p}{\rho_f}} \tag{3}$$

$$\frac{dm_B}{dt} = \rho_v\frac{dV_B}{dt} = 4\pi\rho_v R_B^2\sqrt{\frac{2}{3}\frac{p_v - p}{\rho_f}} \tag{4}$$

where: R_B denotes the radius of the cavitation bubble [m]; p_v represents the saturated vapor pressure within the bubble [Pa]; p is the ambient liquid pressure surrounding the bubble [Pa]; ρ_f and ρ_v correspond to the densities of the liquid and vapor phases, respectively [kg/m³].

The total mass transfer rate between different phases (evaporation or condensation) per unit volume is determined by the relation [37]:

$$\overset{*}{m}_{fv} = F\frac{3\lambda_v\rho_v}{R_B}\sqrt{\frac{2}{3}\frac{p_v - p}{\rho_f}}\,\mathrm{sgn}(p_v - p) \tag{5}$$

where F is an empirical correction coefficient representing the deviation in the evaporation or condensation rate.

The phase change behavior between liquid and vapor is governed by the relationship between the system pressure p and the vapor pressure p_v. Specifically, when $p \le p_v$, the liquid undergoes evaporation, as described by the following expression [37]:

$$\frac{dR_B}{dt} = \sqrt{\frac{2}{3}\frac{p_v - p}{\rho_f}} \tag{6}$$

In contrast, when $p \ge p_v$, condensation occurs, following the relation outlined in the following expression [37]:

$$R_B\frac{d^2R_B}{dt^2} + \frac{3}{2}\left(\frac{dR_B}{dt}\right)^2 + \frac{2\tau}{\rho_f R_B} = \frac{p_v - p}{\rho_f} \tag{7}$$

where: τ is the coefficient of the surface tension between the liquid and vapor in [N·m].

These equations characterize the respective mass transfer processes driven by thermodynamic disequilibrium.

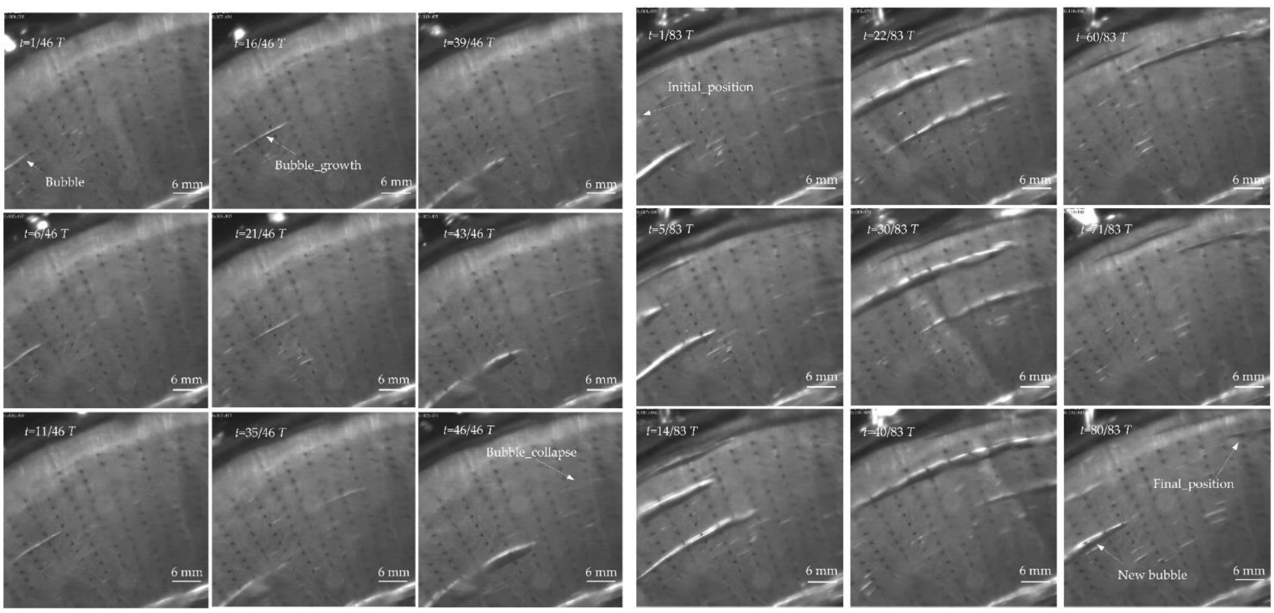

Fig. 3. a) Growth and collapse of cavitation bubbles (direction: clockwise); b) Shedding and regeneration of cavitation bubbles. (Reprinted from ref. [37] with permission of MDPI AG publisher).

The temporal evolution of cavitation phenomena is illustrated in fig. 3a. In contrast, fig. 3b reveals that larger cavitation bubbles exhibit incomplete collapse within the observation cycle. These bubbles expand to their maximum dimension before gradually contracting and eventually exiting the monitoring field. Compared to the smaller-scale structures observed in fig. 3a, the larger bubbles in fig. 3b demonstrate enhanced stability and prolonged persistence, indicating a reduced tendency toward rapid implosion [37].

Donglin Li [8] investigated the differences in tribological performance between carbon fiber-reinforced PEEK (CFRPEEK) and stainless steel under water lubrication, using both a friction testing machine and a water hydraulic axial piston pump.

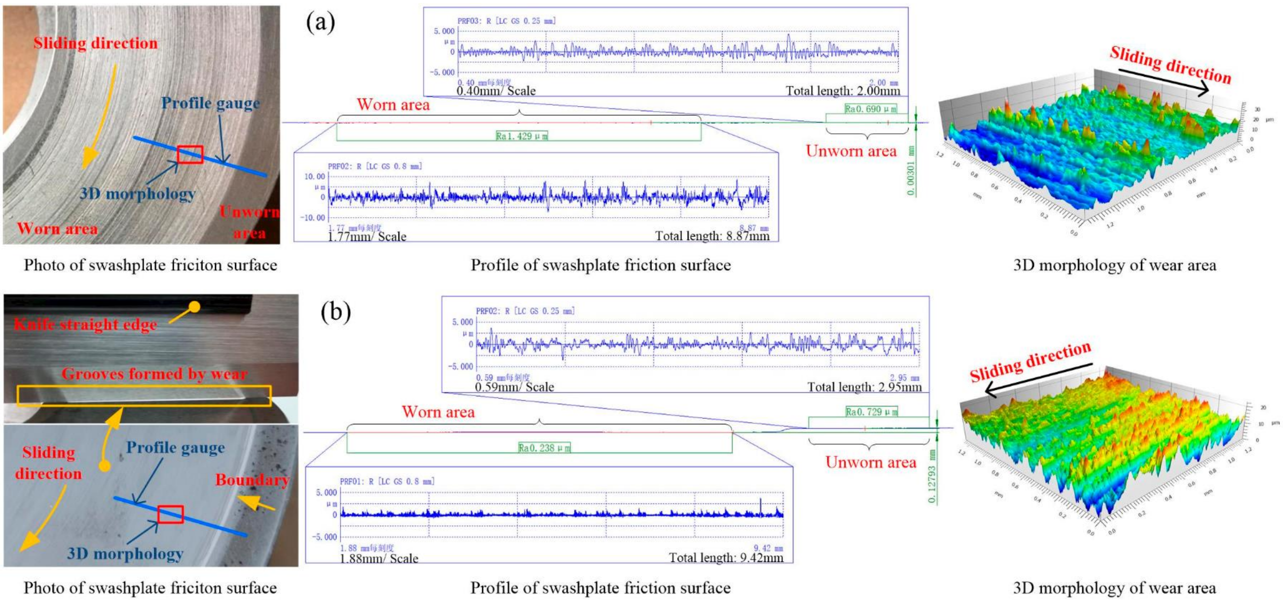

Fig. 4. Wear of friction surface of swashplate parts. (a) The 316L swashplate; (b) the 1Cr17Ni2 swashplate. (Reprinted from ref. [8] with permission of MDPI AG publisher).

As illustrated in fig. 4a, the worn morphology of the 316L swashplate surface reveals substantial material degradation following a brief period of no-load operation. A pronounced groove, aligned with the sliding trajectory of the slipper, delineates a sharp transition between the severely worn zone and the relatively unaffected region, indicating concentrated abrasive action along the direction of motion. In contrast, the friction surface of the 1Cr17Ni2 swashplate, as depicted in fig. 4b, appears considerably smoother. Nevertheless, prolonged operation under high-pressure conditions leads to the formation of noticeable grooves on the surface. A distinct step-like boundary remains evident between the worn and unworn regions, reflecting localized wear progression over time [8].

Figure 5a elucidates the tribological interaction between CFRPEEK and stainless steel counterparts under atmospheric-pressure water lubrication, as simulated in a friction testing apparatus. The imposed load induces interfacial stresses distributed between the semi-crystalline PEEK matrix and its embedded carbon fibers. Given the insufficient pressure of the lubricating medium, neither component undergoes appreciable plastic or elastic deformation; however, the water still fulfils essential hydrodynamic and thermal regulatory functions. Owing to its intrinsically modest hardness and mechanical robustness, CFRPEEK exhibits a comparatively accelerated material loss relative to metallic specimens, though the resulting wear track remains topographically uniform and continuous. Conversely, fig. 5b presents the wear dynamics under high-pressure aqueous lubrication, emulating the operational environment within WHAPs. Such contact dynamics precipitate a metallurgically sensitive wear response: softer alloys like 316L suffer pronounced surface degradation, whereas high-strength steels such as 1Cr17Ni2 demonstrate superior resistance, maintaining a smoother tribo-interface. Moreover, the microstructural roughness of the CFRPEEK surface escalates under these conditions, with metallic debris becoming mechanically entrapped within the more compliant polymeric phase interspersed among rigid carbon reinforcements.

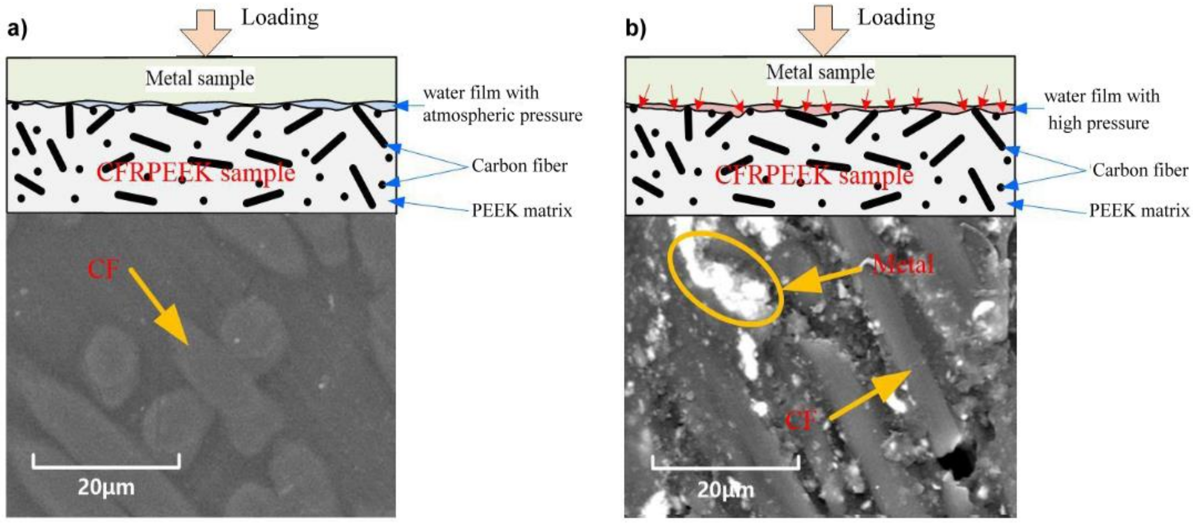

Fig. 5. Comparative wear mechanisms of CFRPEEK and stainless steel under distinct lubrication regimes: (a) atmospheric-pressure water lubrication assessed via friction testing machine; (b) high-pressure water lubrication reflective of operating conditions in WHAPs. (Reprinted from ref. [8] with permission of MDPI AG publisher).

Giorgi et al. [38] studied cavitating flow regimes at varying fluid temperatures through an Artificial Neural Network (ANN) approach aimed at real-time prediction and monitoring. A three-layer Elman neural network was trained using power spectral density data derived from dynamic differential pressure fluctuations measured upstream and downstream of an orifice. The ANN demonstrated strong predictive performance, accurately replicating cavitation patterns confirmed through visual observation. Furthermore, the network enabled identification of frequency ranges most influential to cavitation behavior, as well as the significant role of fluid temperature. Cavitation behavior was found to be influenced by both the cavitation number and temperature. Notably, the transition to the supercavitation regime was more sensitive to temperature changes, with thermodynamic effects becoming increasingly evident at lower cavitation numbers.
Yang et al. [39] investigated the wear reliability of friction pairs in water hydraulic piston motors - key transmission components in water hydraulic systems - by developing a non-probabilistic reliability model based on a convex model approach, which was found to be more economical and practical than the traditional interval model due to the limited availability of experimental data.

4.3 Boundary lubrication and secondary film formation

In tribological regimes where hydrodynamic or elastohydrodynamic film formation is inadequate - typically due to low relative velocity, high contact pressure, or limited lubricant availability - the system transitions into the boundary lubrication domain. Within this regime, the physical separation between contacting surfaces is significantly reduced, often approaching the molecular scale. Consequently, direct asperity interactions dominate the contact mechanics, leading to elevated friction coefficients and accelerated material degradation unless mitigated by auxiliary mechanisms. One such mitigating mechanism is the secondary lubrication effect, which is intricately facilitated by the presence of engineered surface textures. These textures - comprising micro-dimples, grooves, or other concave microstructures - act as micro-reservoirs capable of entrapping lubricating fluid during periods of low or moderate contact stress. During sliding motion, particularly under variable thermal and mechanical loading, the entrapped lubricant is gradually released from these reservoirs into the interfacial region. This release is often promoted by friction-induced thermal expansion of the surface material, which enhances the pressure-driven exudation of fluid or solid lubricants from the textured cavities. Furthermore, the interaction between polar functional groups present in the lubricant and active sites on the material surface leads to the formation of a boundary adsorption film. These films, typically nanometers in thickness, are composed of strongly adsorbed molecular layers - often surfactant-like or containing esters, fatty acids, or phosphate-based additives - that form via physical adsorption or chemisorption. This film serves as a sacrificial interface, accommodating shear deformation and preventing direct metallic or polymeric contact, thereby reducing adhesive wear and limiting micro-welding phenomena. The synergistic action of topographically induced lubricant retention and chemically stable boundary films contributes to a quasi-dynamic lubrication environment. In such systems, secondary lubrication can be viewed as a transitional or hybridized mechanism, oscillating between physical storage-and-release dynamics and chemical film formation. This dual-mode behavior is especially advantageous in water-lubricated or environmentally sensitive systems, where conventional oil-based boundary additives are unsuitable. In water-based lubrication, the importance of surface texture is further magnified due to water's inherently low viscosity and poor load-carrying capacity. Collectively, this interplay between surface texturing, lubricant entrapment, thermally activated release, and molecular adsorption governs the efficacy of boundary lubrication under extreme conditions.

4.4 Wear debris containment and surface protection

In tribological systems operating under dry friction conditions - characterized by the absence of any liquid or semi-solid lubricant phase - the significance of surface topography becomes particularly pronounced. Without the protective mediation of a lubricating film, the entirety of the contact load is borne by the asperities of the interacting surfaces, leading to intensified adhesive and abrasive wear mechanisms. Under such regimes, surface texturing plays a crucial functional role not through hydrodynamic enhancement, but rather as a passive mitigation strategy against progressive surface degradation. One of the dominant wear-related challenges in dry friction systems is the continuous generation of wear debris, which arises from plastic deformation, material fracture, and micro-scale delamination events at the sliding interface. These debris particles, if not effectively removed or sequestered, can become entrapped within the contact zone and serve as third-body abrasives. Their continued circulation exacerbates surface roughness [40], intensifies furrow formation, and promotes the onset of fatigue microcracks, collectively accelerating component failure. To counteract this phenomenon, the deliberate incorporation of concave surface features - such as microgrooves, dimples, or pits - into one or both contact surfaces has proven to be an effective design paradigm. These textural elements function as micro-reservoirs or entrapment zones, selectively capturing and immobilizing wear particulates as they are generated during sliding motion. By isolating debris from the tribological interface, the texture suppresses the recurrence of three-body abrasive interactions, thereby preserving surface integrity and attenuating further material removal. Moreover, the spatial distribution, depth, and geometry of these surface textures critically influence their debris storage capacity and efficacy. Optimized texturing ensures that the entrapped particles are retained under typical loading and vibrational conditions, preventing re-entrainment into the contact path. The result is a substantial reduction in localized stress concentrations and a corresponding decline in the propagation of wear-induced surface defects (fig. 6).

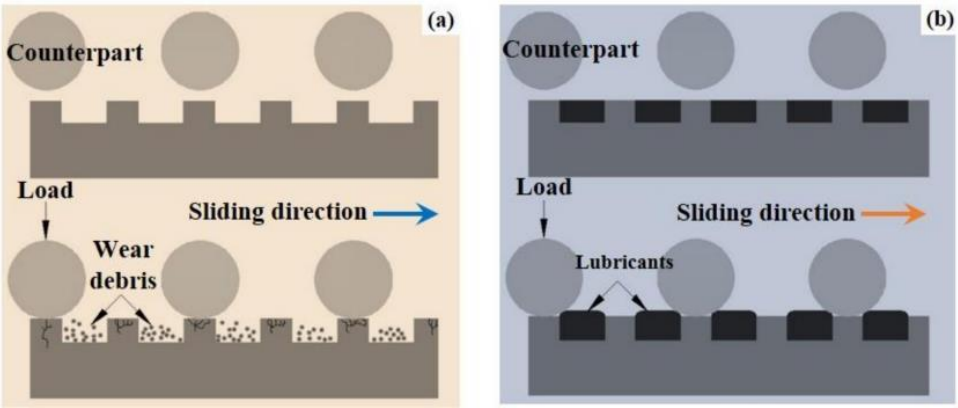

Fig. 6. Schematic illustration of the functional mechanisms of surface texturing in enhancing tribological performance: (a) promotion of continuous lubricant film formation and (b) entrapment of wear debris to reduce abrasive interactions. (Reprinted from ref. [41] with permission of MDPI AG publisher).

Future research should explore adaptive surface textures that respond to dynamic operating conditions, alongside real-time monitoring via digital twin technologies, to enhance wear resistance and prolong WHAPs lifespan in water-lubricated environments.

5. Conclusions

This study highlights the critical tribological mechanisms governing the performance and reliability of water hydraulic axial piston pumps (WHAPs) under water-lubricated conditions. Through a focused analysis of the hydrodynamic effect, cavitation dynamics, and wear debris storage, it is evident that surface texturing plays a multifaceted role in enhancing lubrication stability, mitigating cavitation damage, and minimizing abrasive wear. Engineered textures not only facilitate fluid film formation and pressure stabilization but also serve as effective micro-reservoirs for debris entrapment in boundary and mixed lubrication regimes. These insights provide a foundational understanding for the design of advanced friction pair interfaces in WHAPs.

Conflicts of Interest: The author declares no conflict of interest.
ORCID: Ştefan Ţălu, https://orcid.org/0000-0003-1311-7657.

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