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Investigation on the optimization of sealing and cylinder liner materials for oil-free, high velocity and high-pressure hydrogen reciprocating compressors

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The main challenges associated with the development of renewable hydrogen are hydrogen storage, transportation, and distribution. The utilisation of high-pressure compressed gas tanks is the preferred option for hydrogen storage and subsequent short-term use. Consequently, compressors capable of compressing hydrogen from relatively low inlet pressures (~30bar) to very high pressures (≥ 500bar) are essential. However, in the context of pneumatic piston compressors, the efficiency and durability of the sealing system remains a challenge, particularly in scenarios where these compressors operate at high linear speeds (up to 4 m/s) and high pressures in the absence of lubrication. This study investigates suitable materials for sealing/wear rings and liner components in a hydrogen compressor operating under extreme tribological conditions. The goal is to identify the optimal combination of ring and cylinder liner materials that maximizes compressor durability while minimizing gas permeation for this demanding application. To this end, different materials have been evaluated under operating conditions close to the real ones.

1 Introduction

Hydrogen is increasingly considered a key energy carrier for achieving global decarbonization targets, which has led to a growing demand for efficient and reliable compression technologies for storage and transport systems [1], [2]. Among the available technologies, reciprocating compressors are widely employed in hydrogen refuelling infrastructure due to their capability to reach very high pressures (typically up to 70–90 MPa) and operate under large compression ratios. However, these systems are commonly designed to operate under dry or oil-free conditions, in order to preserve gas purity, which results in extremely demanding tribological conditions. Components such as piston rings, guide rings, and cylinder liners are therefore subjected to high contact pressures, high sliding velocities and temperatures, and cyclic loading, leading to complex friction and wear mechanisms that directly affect compressor durability and efficiency [3].

A major technical challenge in this context lies in the selection and optimization of materials for sealing and guiding elements. High-performance polymers such as polyether ether ketone (PEEK), polyimide (PI), and polyphenylene sulfide (PPS) are widely used due to their favourable combination of thermal stability, mechanical strength, and intrinsic self-lubricating behaviour. In particular, PEEK and PI-based composites reinforced with solid lubricants (e.g., PTFE, graphite, or MoS_2) or fibers have demonstrated improved wear resistance and reduced friction under sliding conditions. Nevertheless, when exposed to hydrogen environments, these materials exhibit additional degradation mechanisms [4], [5], [6]. Hydrogen can diffuse into polymer matrices, modifying their mechanical properties, inducing swelling in some polymers, and significantly altering tribological behaviour. Furthermore, the formation and stability of transfer films, which play a key role in reducing friction under dry contact, are strongly influenced by hydrogen permeation and gas–material interactions. Previous investigations on PI- and PEEK-based sealing materials have shown that hydrogen can substantially modify friction and wear mechanisms. In several studies, hydrogen promoted the formation of carbon-rich transfer films and improved tribological performance compared with air, although hydrogen permeation and material-specific degradation mechanisms may lead to opposite trends under certain conditions [4].

The problem becomes even more critical under dry-running and high-velocity polymer/metal contacts, which are characteristic of reciprocating compressors. In such conditions, the absence of liquid lubrication requires materials to rely exclusively on their solid lubrication mechanisms and the formation of protective transfer films. The performance of these systems is thus highly dependent on the interaction between the polymer composite and the metallic counterface. Under the combined effects of high contact stress, high velocity, and hydrogen exposure, multiple degradation mechanisms including abrasive wear, thermal softening, and hydrogen-assisted damage can occur simultaneously, making material, rings and the compressor design itself particularly challenging. Sealing materials must simultaneously ensure low friction, high wear resistance, and minimal gas permeability [7]. Moreover, non-uniform contact pressure distributions in piston ring systems can further accelerate wear and reduce sealing efficiency, highlighting the importance of optimizing both materials and system design [8].

Despite the increasing number of studies in this field, important gaps remain. Most investigations focus on individual materials or simplified test configurations. While conventional tribological standards are frequently adapted, they do not fully capture the complexity of real compressor conditions, limiting the comparability and transferability of results, and making it difficult to evaluate the combined effect of sealing materials and cylinder liner surfaces under operating conditions representative of reciprocating compressors.

The present work investigates the performance of different polymeric materials and cylinder liner surface solutions intended for use in the sealing system of an oil-free reciprocating hydrogen compressor. High-performance polymer formulations based on PEEK and PI were evaluated as candidate materials for sealing and wearing rings in terms of tribological performance. The most promising formulation was assessed at component level using a dedicated sealing test rig and two different liner configurations: a conventional GG-30 cast iron liner and a tungsten-coated liner. In addition, electrochemical hydrogen permeation tests were conducted to quantify the barrier effect provided by the developed coatings. The objective of the study was to identify material combinations capable of improving both the tribological performance and the hydrogen barrier properties of sealing systems for future high-pressure hydrogen compressor applications.

2 Materials

In this study, three different polymer formulations have been evaluated as potential candidates for sealing and wear ring materials. The materials selected and their main characteristics are shown in Table 1. The compounds were selected based on the real application requirements and bibliographic and market research. The main operational requirements for these materials are that they must be able to withstand high-pressures of up to 500 bar in a hydrogen environment of up to 500 bar, high linear velocities of up to 3 m/s and temperatures of up to +150ºC, in the absence of lubrication.

PEEK (polyether ether ketone) is widely used for seals and wear rings in reciprocating compressors due to its high mechanical strength, excellent wear and abrasion resistance, low friction, and outstanding chemical resistance. It maintains dimensional stability under high-pressure and high-temperature conditions (it can operate continuously at temperatures up to approximately 250–260 °C), minimizes wear against metallic surfaces, and provides long service life in demanding compressor environments. Polyimide (PI) is a type of polymer known for its excellent mechanical and thermal properties, as well as its good chemical resistance. It is commonly used in the production of gaskets, packings, and other sealing products due to its excellent chemical resistance and low coefficient of friction. It stands out for its wide temperature range, which can extend from approximately -195°C to +300°C. As in the case of other polymers, fillers are often added to its formulation to enhance its properties.

For this study, cast iron GG-30 was selected as the reference material for the cylinder liner. This cast iron has an approximate hardness of between 22 and 30 HRC (Rockwell-C). The objective of this project is to develop a coating that reduces the wear on the liner, thereby increasing its durability or service life, while reducing hydrogen permeation through the liner.

Therefore, different combinations of rings and cylinder liner materials have been evaluated in order to identify the optimum material pair for the application.

Table 1: Evaluated polymeric compounds

	Compound		
Property	**PEEK + % carbon fiber + %graphite**	**Virgin polyimide (PI)**	**PI +%graphite**
Tensile strength (MPa)	14	164	65.5
Coeff. Thermal exp. (µm/m/ºC)	54-70	50	49
Hardness	77 ShoreD	100-120 Rockwell M (D785)	E25-45 (D785)
Tmax (ºC)	<260	>350	395

3 Experimental procedure

In order to evaluate the wear resistance of the different proposed sealing/wear ring materials tribological tests were carried out at two different scales: (i) friction and wear tests at laboratory scale and (ii) durability tests at component scale. The tests were performed in air environment. It is worth mentioning that the materials under study may exhibit higher friction coefficients and wear in an air environment compared to a hydrogen environment, due to hydrogen-induced modifications to surface chemistry, transfer film formation and oxidation mechanisms [9]. The hydrogen barrier properties of the cylinder liner material were analysed through electrochemical hydrogen permeability tests.

3.1 Tribological tests at laboratory scale

The tribological performance of the materials under study was evaluated using a rotary "pin-on-disc" configuration under operating conditions representative of the compressor. The aim of these tests was to identify the best combination of ring and housing materials in terms of wear resistance. The tests were carried out in the Triboremedy test rig (see Figure 1) through a three-pin-against-disc configuration, whereby three polymer pins (representing the ring material) are each loaded with F/3 and slide dry on a metal disc (representing the compressor liner) along a circular path. Tests were carried out at speeds of 1-4 m/s and a contact pressure of 0.37 MPa. As the final application is oil-free, no lubrication was used, and forced ventilation was applied to prevent overheating of the polymer. During the tests, friction and temperature were recorded using a thermocouple located near the contact surface. Once the tests were completed, the wear on the pins and disc was evaluated. The tests were divided into three phases (running-in, friction, and wear), each with different operating conditions. Each test was repeated a minimum of two times. The applied test conditions are shown in Table 2.

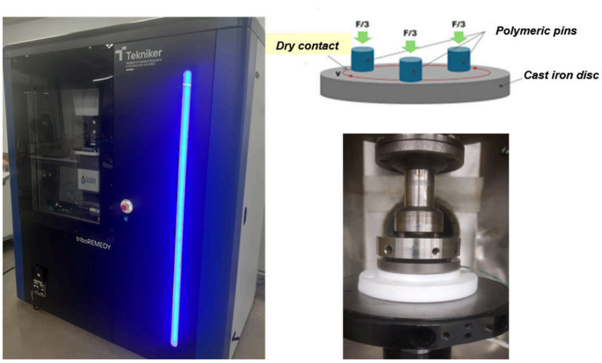

Figure 1: Tribometer and testing configuration

Table 2: Test conditions

	Tribological test					
	Stage	**F (N)**	**P_i (MPa)**	**t (h)**	**w (rpm)**	**v (m/s)**
Running-in	0	50	0.85	3	500	1
Friction test	1	22	0.37	20 min/condition	500	1
	2				1000	2
	3				1500	3
	4				2000	4
Wear test	5			6	1500	3

3.2 Component testing

The aim of these tests is to validate the sealing/wear ring and cylinder liner materials, which were preselected based on laboratory test results, at component level. This will allow to compare the durability of the components under conditions similar to those of the actual application. The tests were performed using the sealing test bench TESSA shown in Figure 2. A tailored est chamber was designed and manufactured to allow testing of a cylinder housing with an inner diameter of 47 mm. The chamber includes a gas inlet to pressurize the system and cooling channels to refrigerate it. It also includes diverse temperature sensors to measure the temperatures reached during the tests in different areas. During the tests, the friction torque generated, the pressure inside the chamber, gas leakages and temperature are recorded.

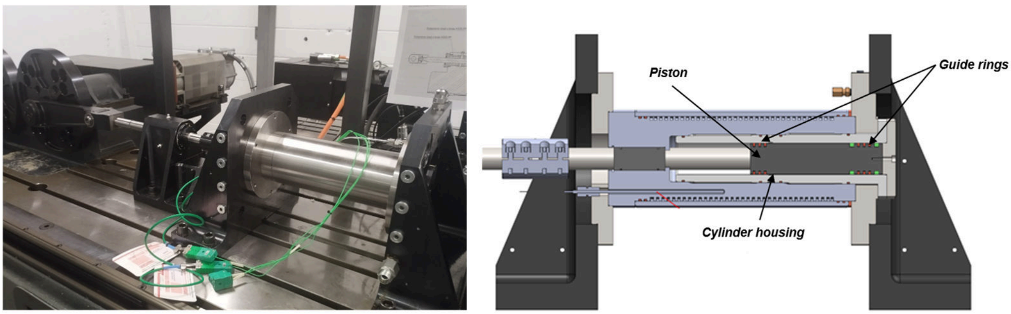

Figure 2: Sealing test rig

Tests were carried out under a sliding velocity of 2 m/s and a chamber pressure of 25 bar of compressed air. Although the initial idea was to use helium to pressurize the chamber, finally compressed air was used due to the high leakage rate of the system, that was specifically designed to measure leakages through the rings, thus avoiding the need of for any additional sealing element. At the end of the tests, wear on the rings and the cylinder housing was evaluated.

Regarding the test conditions, after diverse trials, the test procedure and testing conditions presented in Table 3 were stablished:

Table 3: Component testing conditions

Component tests	
Pressure (bar)	25
Linear velocity (m/s)	2
Stroke (mm)	84
Duration (h)	16

3.3 Hydrogen permeability tests

Electrochemical hydrogen permeation tests were performed on uncoated and tungsten-coated samples using the Devanathan–Stachurski (D–S) cell to evaluate the coatings' barrier effect against hydrogen diffusion. Hydrogen was generated electrochemically on one side of the sample and detected on the opposite side through anodic oxidation, with the measured anodic current corresponding to the permeation rate.

Before testing, a palladium layer was electrodeposited on the detection side to improve hydrogen sensitivity. After stabilising the oxidation cell, hydrogen charging was initiated in an H_2SO_4–KSCN electrolyte, and the anodic current was monitored until saturation. The resulting permeation transients were then analysed to determine the hydrogen permeability and diffusivity of the samples.

4 Results and discussion

In this section, the main results obtained in this study are presented.

4.1 Pin-on-disc test

Figure 3 shows the friction coefficient (CoF) curves obtained during friction tests with different polymeric materials. As can be seen, the CoFs generally decrease with increasing velocity. While the three formulations presented similar CoFs, PEEK and PI+%graphite exhibited more stable behaviour at high velocities (3-4 m/s).

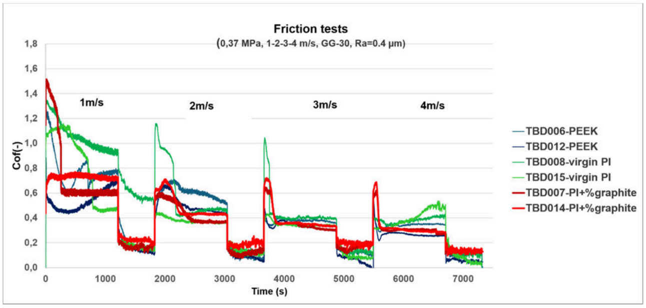

Figure 3: Friction test results

The CoF and temperature evolutions during the wear test for the different materials are presented in Figure 4. As can be seen, virgin PI generated the highest CoFs and PI+%graphite the lowest. In the case of virgin PI steady temperatures in the range of +130-160ºC were measured in the disc, originated by frictional heating, and similar temperatures of up to +100-120ºC were registered for the PI and PEEK compounds.

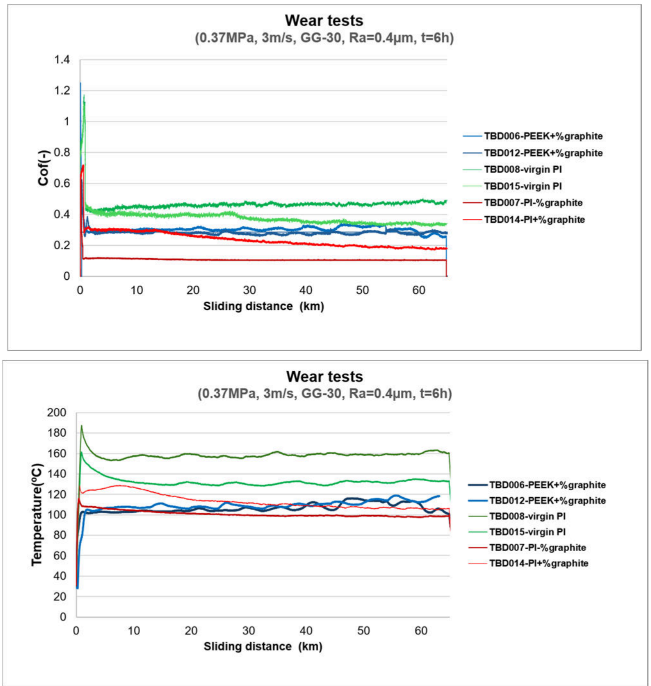

Figure 4: Wear test results

The main wear results of the polymeric pins are shown in Figure 5. As can be seen, Pi+%graphite pins presented the lowest wear rate, followed by the PEEK. In Figure 6 some images of the tested disc surfaces obtained using optical microscopy are shown. The images reveal that material from the PEEK and PI compounds was transferred to the disc surfaces, forming a tribofilm that protects the tribopair.

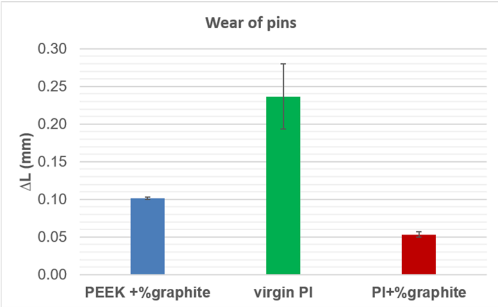

Figure 5: Length loss of the polymeric pins due to abrasion during sliding.

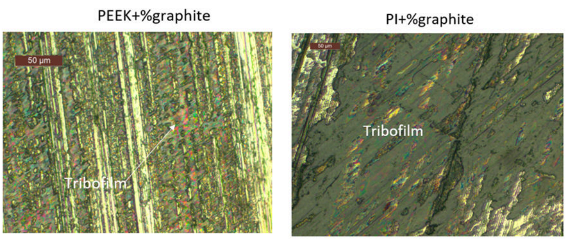

Figure 6: Microscopic image of the wear scars in the discs after the tests

4.2 Component testing results

For these tests, the PI+%graphite compound was selected for the sealing and wear rings. Guide rings and a cylinder liner were therefore manufactured from this compound and GG-30 cast iron, respectively. In addition to the GG-30 cylinder liner, a liner coated with a tungsten (W) coating (with a hardness in the range of 18–20 GPa) was tested to analyse the effect of surface hardness on the results. Tests were carried out in accordance with the procedure presented in Section 3.2.

During testing, the system's behaviour is governed by a strongly coupled thermo-tribological equilibrium between heat generation due to friction, heat dissipation and geometric variations associated with the expansion of the assembly. The measured torque directly represents the frictional force between the piston rings and the cylinder liner, constituting the system's main source of heat generation.

The measured flow rate reflects system leakage, which depends both on the gap between the piston rings and the cylinder liner and on the opening of the piston rings themselves, both of which are sensitive to thermal changes.

It was found that the system presents two very distinct operating phases: (i) a running-in phase and (ii) a steady-state phase.

During the running-in phase, the system operates under highly transient conditions, characterised by high variability in the frictional torque and by forced thermal cycles.

As running-in progresses, the contacting surfaces gradually adapt, reducing the effective roughness and stabilising the friction regime. This process results in a reduction in torque dispersion and more predictable thermal behaviour. Following the transition observed at approximately 28×10⁶ ms (~8h), the system enters a more stable regime, in which the energy balance tends towards a dynamic equilibrium. In this phase, the generation of heat due to friction is periodically offset by heat dissipation, resulting in a controlled oscillating state in which the temperature is maintained within a defined range. The stability observed in the torque, temperature and flow rate signals indicates that the cylinder liner–piston ring assembly exhibits a robust response to forced thermal cycles, with no evidence of severe degradation, suggesting adequate tribological compatibility of the system under the imposed test conditions.

Table 4 presents the mean values of the main parameters measured during the tests. As can be seen, during the running-in phase, the two combinations tested produced similar friction torques and leakages, and the external cooling had to be activated the same number of times because high temperatures were reached. In the steady phase, however, the coated cylinder liner resulted in higher friction torques and therefore required more refrigeration.

Table 4: Mean results of the component tests

	GG-30 vs. PI+%graphite		**W vs. PI+%graphite**	
Property	**Running-in**	**Steady phase**	**Running-in**	**Steady phase**
Friction Torque (Nm)	14.4	9.26	14.43	14.17
Leakages (l/min)	4.61	4.06	4.14	4.29
nº of necessary coolings	10	2	10	11

After the tests, a surface analysis was carried out on both the cylinder liners and the piston rings. In Figure 7 the average thickness loss due to wear of the tested sealing and wear rings is shown. Each numbering corresponds to the position of the ring as shown in the image. As can be seen, although the frictional torque generated by the coated liner is greater, in terms of wear, the wear caused to the sealing rings and carrier rings is similar or lower in all cases, particularly in the case of the carrier rings which slide at a higher contact pressure than the rest.

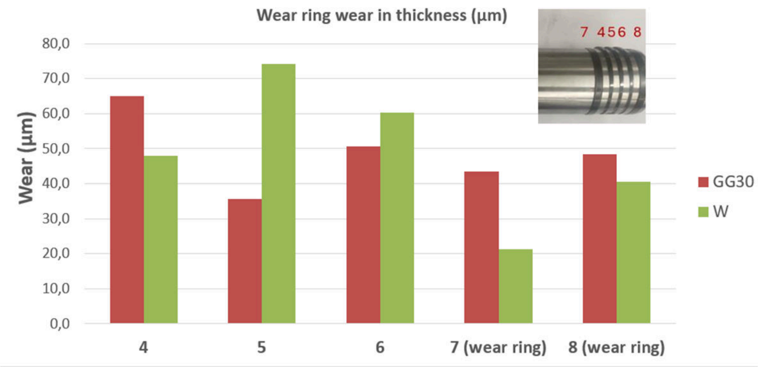

Figure 7: Mean wear of the tested sealing and wear rings.

4.3 Permeability results

In Table 5 the main results pf the permeability tests carried out onto coated and non-coated steel samples are presented. Results showed that the deposited tungsten coatings are able to reduce to the minimum the permeation. Compared to uncoated steel, the permeation flux decreases by approximately two to three orders of magnitude.

Table 5: Saturation current density (Jp) and permeability (Φ) obtained from the tests. For coatings, the average value of the permeability reduction factor (PRF) is included.

	Jp(µA/cm^2)	**ϕ(mol x m^-1 x s^-1)**	**mea PRF**
AISI 4130 (no coating)_1	130	$1.2\ x\ 10^{-8}$	/
AISI 4130 (no coating)_2	138	$1.3\ x\ 10^{-8}$	/
W coating_1	0.15	$1.4\ x\ 10^{-11}$	893
Wcoating_2	it does not reach the threshold of 0.1 µA/cm^2		

5 Summary and Conclusions

The development of hydrogen storage and distribution infrastructures requires reliable oil-free reciprocating compressors that can operate under severe tribological conditions, including high pressures, elevated sliding velocities, and demanding sealing requirements. This work evaluated the performance of several high-performance polymeric materials for sealing and wear rings, together with coated cylinder liners, for application in high-pressure hydrogen compressors. The assessment combined laboratory-scale tribological testing, component-level experiments, and hydrogen permeability measurements.

Pin-on-disc tests showed that friction coefficients generally decreased as sliding velocity increased. Among the evaluated materials, the graphite-filled polyimide (PI + graphite) exhibited the best overall tribological performance, combining low friction values with the lowest wear rates. Based on the laboratory results, the PI + graphite compound was selected for component-scale testing. The sealing system showed a clear running-in stage followed by a stable operating regime characterized by consistent torque, temperature, and leakage values, demonstrating good compatibility between the polymer rings and the cylinder liners. While the tungsten-coated liner generated higher friction torque than the conventional GG-30 cast iron liner, it produced similar or lower wear on the sealing elements, particularly under the most demanding contact conditions. Hydrogen permeability tests demonstrated the effectiveness of tungsten coatings as barrier layers. The coatings reduced hydrogen permeation by approximately two to three orders of magnitude compared with the uncoated reference material, while also providing high surface hardness and enhanced protection against wear.

Although the testing methodology reproduced the mechanical and tribological operating conditions of the compressor, the experiments were performed in air and compressed air environments. Since hydrogen can significantly modify friction, wear, transfer-film formation and polymer degradation mechanisms, the proposed material combinations will be further validated in a compressor prototype.

Overall, the results indicate that compressor durability depends not only on the intrinsic properties of the sealing materials but also on the optimization of the tribological pair, including liner hardness and surface characteristics. The combination of graphite-filled polyimide rings and tungsten-coated liners emerged as the most promising solution, offering an advantageous balance between wear resistance, operational durability, and hydrogen permeation resistance. These findings provide valuable guidance for the development of next-generation oil-free hydrogen compressors with improved reliability and service life.

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