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Improving the performance of a proportional 4/3 water–hydraulic valve by using a diamond-like-carbon coating

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A B S T R A C T

Today, there are several water–hydraulic, power-control systems already available on the market. Their components are usually made of stainless steel, which ensures satisfactory performance under mild, conventional operating conditions. However, for more demanding operating conditions and long-term, low-friction and low-wear performance, they do not provide the required performance. One of the possible ways to improve the performance of stainless-steel components in water–hydraulic systems is to coat them with diamond-like carbon (DLC), since this material is well known for its excellent low-friction and low-wear characteristics and also provides very good performance under water-lubrication conditions. In this study, real-scale lifetime tests with 2.3 million cycles were performed on a hydraulic test rig with a proportional 4/3 directional control water–hydraulic valve. Two types of contacts in the valve were tested: the steel-spool/steel-sleeve and the DLC-spool/steel-sleeve. The wear behaviour of the valve was evaluated with a scanning electron microscope (SEM) and internal leakage measurements. In the real-scale lifetime tests the wear and the damage on the DLC-coated spool were significantly lower than on the steel spool. Furthermore, in agreement with this, the internal leakage in the DLC-spool/steel-sleeve valve was almost constant throughout the tests, while in the steel-spool/steel-sleeve valve the leakage slowly, but steadily, increased. The steel/steel and DLC/steel contacts were also separately evaluated in pin-on-disc model tribological tests under water-lubricated conditions for a comparison and for a better understanding of the tribological mechanisms. In agreement with the real-scale tests, the DLC/steel contact showed improved friction and wear performance in comparison with the steel/steel contact.

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1. Introduction

Protection of the environment has become increasingly important over the past few decades. As awareness about the harmful effects of conventional mineral/synthetic oil lubricants and chemical additives on the environment has increased, one of the main challenges in the industry has become the introduction of alternative, natural-source lubricants into various mechanical systems, including hydraulic systems. In power-control hydraulics there are currently two main approaches to the development of environmentally adapted and sustainable systems. The first one is the use of bio-degradable oils in classic hydraulic systems [1], which partially solves the problem, but bio-degradable hydraulic oils usually contain some chemical additives that are not completely harmless [2]. The other option, which is even less harmful for the environment, is the use of water as the hydraulic fluid. However, due to the low viscosity and poor lubrication properties of water its application is associated with potential risks of higher wear and friction and requires several modifications to conventional hydraulic systems [3–5].

Today, several commercially available water–hydraulic valves are already present on the market. These are relatively simple, conventional, hydraulic valves; however, continuously controlled, hydraulic valves, which are essential for the majority of today's hydraulic machinery, are still under represented on the market. This is due to the fact that water–hydraulic systems are not advanced enough to satisfy the demanding requirements in these systems and applications [6]. Recently, we have designed a new, proportional 4/3 directional control water–hydraulic valve and tested it in a real-scale lifetime test [7]. All the main components are made of hardened stainless steel. The characteristics of the stationary [8,9] and dynamic [10] behaviour of the water power-control hydraulics were already examined and compared with the performance of oil hydraulics. The results showed the excellent behaviour of water–hydraulic systems, which were comparable with oil hydraulic systems. However, in the experiments it was noticed that stick-slip occurred between the spool and the sleeve

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in the water–hydraulic valve and that wear could represent a problem for even more demanding operating conditions [8–10].

One of the possibilities to further improve the performance of the steel components in a water–hydraulic valve is to coat the components with diamond-like carbon (DLC). These coatings are well known for their excellent friction and wear properties, primarily in dry and oil-lubricated conditions [11–16]. However, the very early studies of DLC coatings sliding in water tended to report the unsuccessful operation of hydrogenated DLC coatings with a relatively high friction, while hydrogen-free coatings performed much better, with very low wear and friction between 0.04 and 0.1 [17–19]. However, later studies showed that hydrogenated DLC coatings can also provide good wear performance with typical wear rates of around 10^{-9}–10^{-7} mm^3/Nm and a friction close to 0.1 or slightly higher [20–25], while sometimes the friction was even lower, between 0.05 and 0.1 [26–29]. These studies, mainly performed in steel/DLC contacts [20–24,26–29], a very common combination in many applications, have shown that the beneficial effect is due to tribochemical films formed on the steel and DLC side in these contacts [20–24,27,28]. Therefore, these are very promising values and findings for industrial applications and lay grounds for further investigations of application-oriented studies in real-scale contacts.

Accordingly, in this study a DLC-coated spool against a steel sleeve valve was evaluated under real-scale, long-term, water–hydraulic operating conditions. A test involving 2.3 million cycles was performed; this corresponds to 6 months of operation for 8 h per day in a typical hydraulic system. The performance of this valve with its DLC coating was compared to the same, all-steel valve under the same, long-term, real-scale conditions. To further verify and better understand the tribological behaviour of these two contacts under water-lubricated conditions, more controlled, model-tribological tests of steel/steel and DLC/steel contacts were also performed. The results from both tests were very favourable for the DLC/steel contact pair under water-lubrication conditions.

2. Experimental

2.1. Materials

In real-scale, lifetime hydraulic tests under real operating conditions two water–hydraulic valves were tested: a steel-spool/steel-sleeve valve and a DLC-spool/steel-sleeve valve. The spools and the sleeves were made of martensitic, hardened stainless steel (SIST EN X105CrMo17) and were heat treated to a hardness of 55 HRC. In the DLC-spool/steel-sleeve valve, the spool was coated with a commercially available, amorphous, hydrogenated, DLC coating (Sulzer Sorevi SAS, France). It was deposited using a hybrid PVD/CVD process, i.e., a radio-frequency, plasma-assisted, chemical-vapour-deposition process. A thin Si-based interlayer was used to improve the adhesion of the coating, which had a thickness of about 1.8 μm. The properties of the DLC coating, as described by the producer, are given in Table 1. The roughness of the spool and the sleeve was always 0.25 ± 0.15 μm and the internal clearance was about 1.75 ± 0.7 μm, which are less than the typical values for the oil components. However, materials with better quality were selected so as to have approximately the same (theoretical) internal leakage values as with the comparable reference oil systems.

Table 1
Properties of the amorphous hydrogenated DLC coating.

Deposition process	RF PACVD (13.56 MHz)
Thickness (μm)	1.78 ± 0.09
Hydrogen (H) content	30 at%
Adhesion promoting interlayer	silicon (Si) based
Hardness (GPa)	21.9 ± 0.5
Young modulus (GPa)	157.4 ± 2.2

The model tribological tests were performed using the pin-on-disc testing geometry. The pins and the discs were made of the same martensitic, hardened stainless steel as the spool and the sleeve. Some of the discs were used as steel specimens in the tribological tests, while some of the discs were coated with the same amorphous hydrogenated DLC coating as the spool (Table 1). The diameter of the pins was 10 mm and the discs were 8 mm high with a diameter of 24 mm. The surface roughness R_a of the pins and the discs was 0.05 ± 0.01 μm, as measured with a stylus tip profilometer (T8000, Hommelwerke, Germany).

2.2. Lifetime hydraulic tests under real operating conditions

Lifetime hydraulic tests were performed on a twin-type hydraulic test rig, which is in detail described in earlier publications [30,31]. It consists of a hydraulic tank, a high-pressure water pump, a pressure filter, a proportional 4/3 directional control water–hydraulic valve and two dumpers with a diameter of 1.5 mm. The dumpers were used for simulating the load in the long-term test. The test rig is equipped with pass filtering and cooling. Most of the test rig parts are commercially available, except for the proportional 4/3 directional control water–hydraulic valve, which was designed in our laboratory. The test rig is equipped with measuring and control equipment and the data acquisition is implemented using LabView software (National Instruments, USA).

Fig. 1a shows the proportional 4/3 directional control water–hydraulic valve, the actual testing sample in this work. The two major parts that are mainly exposed to wear and significantly affect the friction are the sliding spool and the housing sleeve (Fig. 1b). Other parts of the valve consist of the springs, the outer housing, the adaptors for the proportional solenoid, and two proportional solenoids, one of them equipped with an inductive transducer (Fig. 1a).

The internal leakage of the valve ($Q_{L,\max}$) was calculated with the equation for reference oil systems, [32]:

$$Q_{L,\max} = n_{ip}\left[\frac{\pi}{12}\frac{\Delta p D_m s^3}{\rho \upsilon L} f_{ecc}\right]$$

where n_{ip} is the number of leaving cross-sections, Δp is the pressure difference in the gap, D_m is the middle diameter between the hole (sleeve) and the pin (spool), s is the gap between the spool and the sleeve in the centric position, ρ is the specific gravity, v is the kinematic viscosity and f_{ecc} is the factor of eccentricity.

Real-scale lifetime tests were performed with 2.3 million cycles, which corresponds to 6 months of operation for 8 h per day at maximum load with a frequency of 1 Hz. The working temperature was 40 °C and the maximum inlet pressure on the port P (Fig. 1b) was set to 160 bar. The frequency of the spool was 5 Hz and the amplitude was set to $\pm 100\%$, which is equal to 3 mm. Distilled water was used as the hydraulic liquid in all the tests.

Measurements of the internal leakage of the proportional 4/3 directional control water–hydraulic valve were performed after every 100,000 cycles in the early stage of the test and after every 200,000 cycles in the later stage of the test. An internal leakage of 100 ml/min was considered as acceptable, as this is the same as in typical oil valves. Namely, the internal leakage should remain lower than 1% of the maximum fluid flow during the test. Each measurement was repeated at least three times in order to ensure

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