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PERFORMANCE OF AXIAL PISTON PUMP USING DLC-COATED PISTON SHOES AND BIODEGRADABLE OIL

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ABSTRACT

A hydraulic axial piston pump with DLC-coated piston shoes was tested in a system using fully formulated biodegradable synthetic ester oil. For comparison, equal, but separated system was tested with the conventional commercial pump having steel shoe surfaces. A dedicated test rig was developed for this purpose. Results show that at the 85 % of nominal pump load and oil temperature around 80°C, both systems performed satisfactory in the period of 2000 hours, which correspond to more than one year of continuous operation in application. Severe oxidation of the oil did not occurred in any of the system, but the oil from the circuit comprising the DLC-coated shoes showed slightly – but consistently better results. The wear of the DLC-coated shoes, especially during the running-in, was remarkably lower than in conventional system. Only minor polishing wear was observed at the DLC shoe sliding surfaces, while in steel shoe surfaces many scratches were found and some edge erosion was detected. However, the leakage of both systems was small and overall wear performance was satisfactory, too.

1. INTRODUCTION

Environmental awareness plays more and more important role in selection and development of technical systems. This especially includes machines and systems used in forests, agriculture, mining, construction, etc. Lubricants and lubrication are one of the major concerns with this respect. It was estimated that about 10% of all the lubricants used in Europe are exposed to natural surroundings [1], which increases the already high level of pollution. In many countries and regions legislation or even customers require technical systems with the appropriate solution for the environmental care. For example, biodegradable oils can offer one of the solutions to the above problems. The common biodegradable oils are natural, i.e., rapeseed oil or sunflower oil, and synthetic esters. Natural biodegradable oils possess good anti-wear properties and low friction. However, their oxidation and thermal stability is poor, and this is their major drawback [2]. On the other hand, synthetic esters are more resistant to oxidation and thermal degradation, but their tribological properties are not as good as those of natural esters. Namely, some of the conventional (metal) boundary lubrication mechanisms are due to the adsorption of oil/additive polar groups at the oxidized metal surface and biodegradable oils contain high amount of these groups. Accordingly, this high number of polar groups improves the tribological performance of conventional metal tribo-systems, but also causes oil oxidation, especially at high temperatures. Any reduction in oil temperature can thus help to reduce the oxidation and prolong the lifetime of these oils.

DLC coatings are known to provide low friction and consequently lower heat generation and system temperatures even under dry conditions [3]. Their beneficial effect on reduced temperatures was found also under lubricated conditions in real-scale applications [4]. Moreover, DLC coatings can also protect the surfaces against excessive wear, as broadly reported. Therefore, the combination of DLC coatings and biodegradable oils can have two positive effects: (i) to protect the mechanical parts against the wear, and (ii) to prolong the life-time of the lubricant. However, the DLC coatings are more inert and are less prone to react with the oils and additives than steel. However, in recent years it was clearly shown that both, doped and non-doped DLC coatings can react with the additives [5,6] and that polar and saturation characteristics of base oils play an important role, too [7]. However, the effectiveness and behaviour of a combination of biodegradable oils and DLC coatings are still not well evaluated under conditions in real mechanical components, in particular in long-term operation, where the oxidation degradation of oils can be realistically evaluated.

In this work we have focused on the evaluation of performance of "environmentally adapted" axial piston pump that is commonly used in many hydraulic systems exposed in natural environments. We have introduced the DLC coatings to the surfaces that are one of the most sensitive for high wear in this pump, i.e. piston shoes, and we have lubricated the pump by in-house developed biodegradable synthetic ester. A 2000-hour test, which corresponds to one year of continuous every-working-day operation, and is close to expected life-time of vegetable oil in such system, was performed in a newly developed hydraulic test rig. For comparison, the same experiment was simultaneously performed in a pump without coated surfaces, but using the same oil.

2. EXPERIMENTAL

Axial piston hydraulic pump was selected for the testing system in this study. There are few parts in this pump that suffer from excessive wear, however, contact between the piston shoes and swash plate is one of the most critical. Figure 1 shows the assembly of nine piston shoes and assembling plate inserted in cylinder block. In our test configuration, the front sliding surface of the piston shoes were DLC-coated, while the rest of the shoe was carefully protected against access of any deposition influence, in order to allow the same motion capability of the shoe head and the same tolerances of the moving parts, as without coated surfaces. The DLC coating was a multilayer WC/C structure, prepared by a reactive magnetron sputtering. The coating consists of two types of 50-100 nm thin lamellas, rich in WC and C, respectively. The adhesion promoting interlayer is about 0.13 µm thick, consisting of pure (> 99%) Cr. The total coating thickness was about 2.6 µm. The oil used was a fully-formulated in-house developed synthetic saturated complex ester having viscosity grade ISO VG 46 and viscosity index 138. The oil was formulated for typical hydraulic application, including anti-wear additives, friction modifiers and antioxidants, in order to satisfy load-carrying properties in a standard FZG test (DIN 51354-2).

A new test rig (Figure 2) that consists of two equal, but separate hydraulic circuits was designed and constructed. Each circuit consists of major parts: original or modified (DLC) axial piston pump (Vickers PVB5 RS Y 40 C 12,) as a testing unit, a drive motor, oil reservoir, own (separate) amount of lubricant, an oil-flow regulation pressure compensating valve, hydraulic pressure valve, by-pass system for on-line oil-leakage measurements and oil sampling, cooling system, filter (grade 25 µm), and regulation. Oil temperature, a key-parameter for oil oxidation stability, was controlled by regulation system with a cooling chamber. In one separate testing system (circuit) the head of the piston shoes in the pump were DLC-coated, as described above, while in the other no modifications were made to the commercial pump, i.e. conventional contacts were used.

Before the experiments, each piston was marked for position in the cylinders and weighted. The reservoirs and pipes were cleaned with the same oil as used in the tests, which was than removed after cleaning. Prior to actual experiments, a 25 l of fresh oil was put in each separated system.

Figure 1: Assembly of pistons with DLC-coated shoes, inserted in pump cylinder block.

The pump load (pressure) was set to 85% of its maximum value, i.e. to 180 bar (shoe contact: p=15 N/mm^2, v=3.4 m/s). By use of the cooling system, the oil temperature during operation in both pumps was controlled and maintained in the range form 81-86^{o}C, while the oil temperature in the reservoir was between 70 and 75^{o}C. The pump flow into the pressure line was 6 l/minute. The testing conditions were first stabilized to equal values in both systems and then the tests were started and simultaneously run for total of 2000 hours. Pump leakage of the leakage line was measured after 3, 300, 400, 500, 750, 1250, 1750 and 2000 hours, by measuring amount of oil that was collected within 30 seconds at the by-pass system, just prior the stop of the system due to dismounting and wear analyses, where these two analyses coincide. After 500 hours the test was stopped, the parts were dismounted and the surfaces were visually inspected and photographed. Each piston was weighted separately and the wear loss of the whole set was used as a wear result/criteria. The same procedure as after 500 hours was repeated after 750, 1000, 1500, 1750 and 2000 hours. After examination, the pump was mounted again and the test was continued. Total acid number (TAN) and kinematic viscosity of the oil, using the titrimetric analyzer Mettler DL25 and Cannon-Fenske capillary viscometer, respectively, were measured before the test and after 500, 1000, 1500, 1750 and 2000 hours, in order to monitor the oxidation rate of the oil.

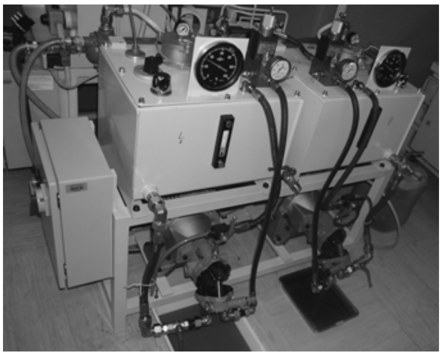


Figure 2: A hydraulic piston pump test rig with two separate testing systems (circuits).

3. RESULTS

Figure 3 shows a total wear of a whole set of nine conventional and DLC-coated piston shoes within the pump. It is clear that wear was the highest in initial 500 hours, and it was about two times higher for conventional than for DLC-coated shoes. At 750 hours and later, the wear of both systems become stable and similar, irrespective whether shoes were coated or not. The wear between all the analysed periods after 500-hour evaluation was about 10 times lower compared to wear measured in initial period of 500 hours. It appears that running-in phenomena are responsible for the most of the wear and that the running-in was particularly beneficial and less severe for the DLC-coated than for conventional system. Nevertheless, after 2000 hours both systems still operate at the same wear-levels, without any distinctive increase in wear.

The contacting surfaces of the piston shoes are mainly in agreement with the wear data; however, there are some qualitative differences between the conventional and DLC-coated shoes clearly found. After 500 hours, almost no changes can be seen at the DLC shoes, Figure 4a. Grinding scratches from preparation of samples/piston shoes are still visible and coating was covering the whole surface, i.e. no spalling or major wear signs were observed. However, there is a distinctive circular region seen at the shoe surface, most probably representing the area of more intense contact against the swash plate. On the other hand, many scratches in various directions could be seen on the steel shoes, indicating abrasive damage, Figure 4b. Several larger scratches are also observed, which agrees with the higher and more severe wear during running-in and also higher measured wear loss (Figure 3).

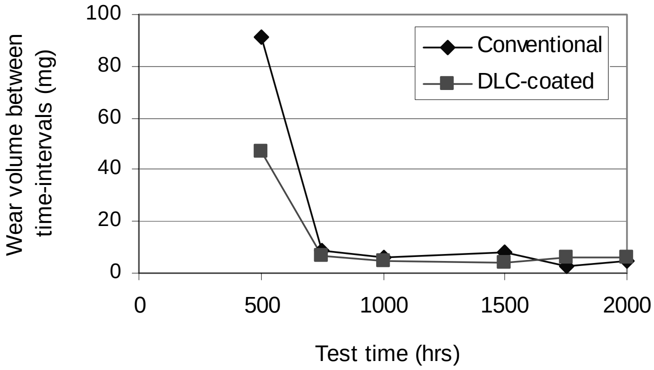


Figure 3: Wear volume of the set of the conventional and DLC-coated shoes.

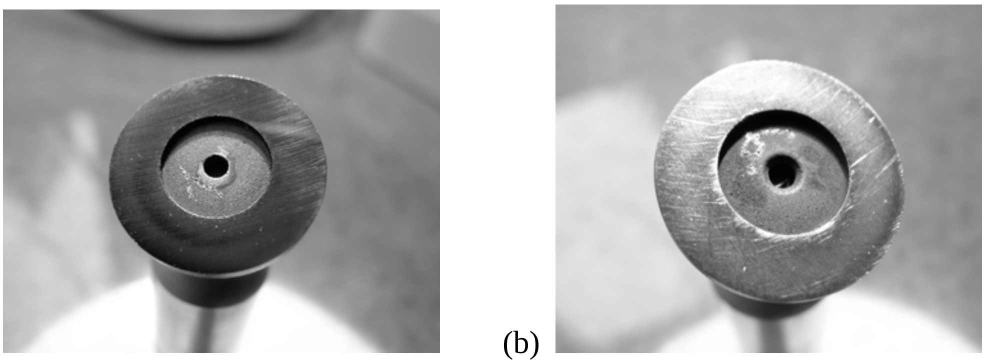
(a)  (b) 

Figure 4: A photograph of the shoe front-surfaces after 500 hours on (a) DLC piston shoe, (b) steel piston shoe.

Figure 5 shows the piston shoe surfaces after 750 hours of testing. Again, practically no changes can be seen on DLC-coated shoes, still showing the grinding scratches with their orientation from the shoe manufacturing process (Figure 5a). On the other hand, the conventional steel shoes have many scratches at the surface, but in various directions (Figure 5b), the same as after 500 hours. In addition, damage at the inner edge of the sliding surface is also well observed and pronounced. This is a typical erosion damage of the shoe in this type of pump, caused by the abrasive particles in the oil. Since there was a lot of wear observed in this system during initial stage (see Figure 3), most probably the wear particles that generated during running-in hit the edges of the shoe at high speed and provoke this erosion wear. This type of wear is dangerous for the increased leakage and reduced power efficiency, if the amount of eroded edges increase excessively with time. Therefore it is essential to reduce the amount of wear and amount of wear debris in the pump that can cause this type of damage. Accordingly, the low wear observed with the DLC-coated shoe surfaces is beneficial also due to the reduced risk of erosion wear, not only the abrasive wear of the shoe front surfaces.

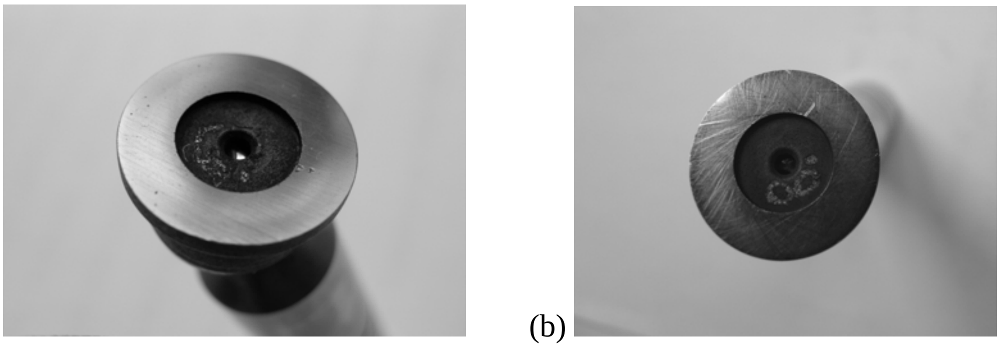
With increasing number of testing hours, the appearance of the surfaces did not change significantly until the end of the test after 2000 hours. However, most of the DLC-coated shoes were slightly worn and very smoothened, which suggests a mild wear regime during test for these surfaces. No wear-through or spallation of the coatings was observed. Few DLC-coated shoes, however, showed small pits at the surface, Figure 6a.

It is believed that this is due to the columnar structure of this particular coating and might indicate the initial stage of subsequent excessive wear at those points - if the test would continue. Nevertheless, after 2000 hours, the coating and the whole system seem to still perform very well.



(a) (b)

Figure 5: A photograph of the shoe front-surfaces after 750 hours on (a) DLC piston shoe, (b) steel piston shoe.



(a) (b)

Figure 6: A photograph of the shoe front-surfaces after 2000 hours on (a) DLC piston shoe, (b) steel piston shoe.

On the other hand, steel shoes have a numerous scratches at the front surface in various directions (Figure 6b), indicating that these are a result of wear, not the sample preparation, as found and commented previously. It seems that at several steel shoe surfaces the amount of scratches increased/accumulated and some of them were very pronounced. However, overall, the severity of the wear and form of abrasive damage did not increase significantly and the failure mode did not change, neither. According to wear data (Figure 3), the operation of this pump also seems to be acceptable.

Leakage was measured at several time intervals during operation of the systems, typically just prior the stop of the system. From Figure 7 it can be concluded that leakage did not change significantly in the testing period, compared to initial inherent leakage of the pumps. The variation of the data is reasonable and within the expected scatter. Namely, since the leakage is proportional to the gap in the contact to the third power, it is clear that gaps in tested systems did not change significantly during the testing time (even a very small change in gap would result in a larger difference in leakage of few percents). Moreover, a consistent trend that would indicate a wear-related leakage was not observed. It can also be seen than the variation between the conventional and DLC-coated system is negligible and within the measurement error. This is in agreement with the wear data and observation of the surfaces, suggesting that both systems performed well also at the end of the test and that the wear did not progress significantly, especially not the erosive wear of the shoe edges, which typically lead to increased leakage.

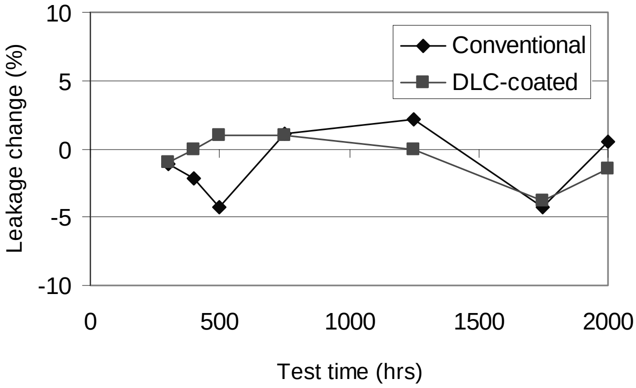


Figure 7: Leakage of the oil in the pump with the conventional steel and DLC-coated shoes, compared to initial/inherent pump leakage.

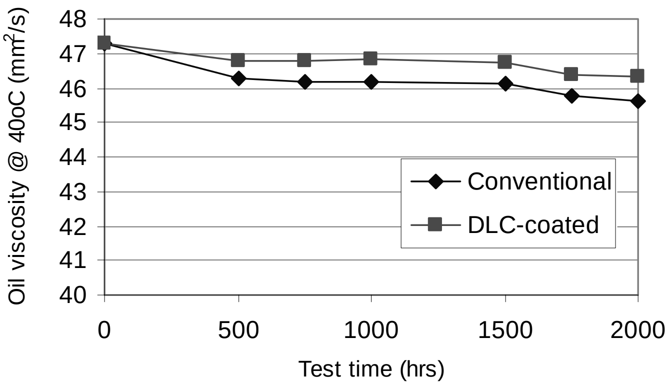


Figure 8: Kinematic viscosity of the oil in systems with conventional and DLC-coated piston shoe surfaces during the 2000-hour test.

Viscosity of the oil, which indicate oxidation when increases, was rather stable during the experiment, since the change of about 1-2 mm^2/s can be considered as small, Figure 8. The difference was even smaller for the oil from system with DLC-coated shoes. A slightly more significant change was observed in the initial 500 hours for the conventional steel system. In this initial stage, the decrease in viscosity of biodegradable oils is expected due to molecule rearrangements, which is quite common in such systems and does not provide indication/correlation to oxidation of the oil. Moreover, based on the measured results, it appears that severe oxidation of the oil did not start during the whole test of 2000 hours, because an increase of about 10 % would be expected for such conclusion. In fact, the viscosity should increase to suggest the oxidation of the oil, not decrease, as is the case in present experiments. The reason for this decrease, however, is not clear yet, but due to very low variation/change, it is most probably a result of measurement inaccuracy, which can be due to other environmental and measurement effects over such a long period, i.e. 2000 hours. Nevertheless, it is interesting that the oil from the system with DLC-coated surfaces consistently provide lower change in viscosity than oil from conventional system.

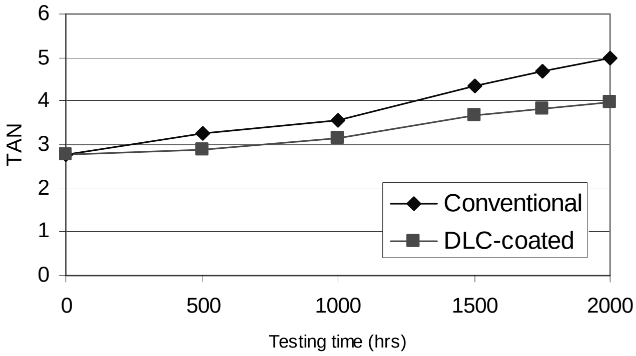


Figure 9: Total acid number (TAN) measurements of the oil for conventional steel and DLC-coated piston shoe surfaces during the 2000-hour test.

The results of the total acid number (TAN) measurements are presented in Figure 9. The TAN values for both systems increase steadily. The changes are not very high, but indicate partial oxidation of the oils. However, since the amount of fatty acids, which are the most sensitive for these changes is very high in the ester oils, it is expected that some of them would degrade and TAN would slowly increase over time. However, there was no significant or sudden change measured, which is typical for critical degradation of the oil due to severe oxidation. This agrees also with the other results, presented above. However, similar to viscosity data, it can be noticed that the system with the DLC-coated shoes show about two-times lower change. Despite this, the conclusion on actual improvement in TAN results due to use of the DLC-coated surfaces is not straightforward and might be questionable due to steady and slow increase and also due to relatively small differences. However, these TAN results suggest a satisfactory behaviour of both systems (in particular DLC-coated), and confirm that a significant/critical change in oil oxidation throughout the 2000-hour test did not occur.

4. DISCUSION

The results report on 2000-hour test of two equal, but separate hydraulic systems that included axial piston pump, which corresponds to operation of one year of every-working-day in real application. One of the pump contained piston shoes that were DLC-coated, while the other had commercial conventional steel shoes. A target of this study was to investigate the performance of the system that included biodegradable lubricant in combination with the DLC-coated parts, in this case piston shoes. The results indicate that both systems operated very well in the selected period at about 85

% of maximum load, i.e. 180 bar. From the results it is obvious that the coated surfaces did not wear-out or experience any catastrophic wear mode, such as spalling or detachment. On the contrary, only minor polishing-type of wear with smoothening of the surfaces occurred under selected conditions. The most of wear for conventional system, that was about two-times higher than that of the coated one, was observed only in the initial 500 hours, obviously during running-in, Figure 3. The wear debris that were generated in this system during running-in, most probably caused abrasive wear scratches at the front shoe-surfaces (Figures 4-6), but also erosive wear of inner ring edges (see particularly Figure 5), which are seen in presented images. The abrasive scratches were visible at all test intervals, and it seems that they accumulated during the test: see the increased amount of scratches at Figure 6b. On the other hand, no scratches or any other sign of wear, except smoothening, were found at the coated shoe surfaces. Indeed, there were some pits observed at the end of the test (Figure 6a), which might indicate that the coating wear was already high enough to provoke some surface defects due to specific columnar structure of this coating, which could subsequently lead to more severe wear. However, up to the tested stage of 2000 hours, this did not occur. Accordingly, the use of DLC-coated resulted in reduced amount of wear and better running-in performance compared to conventional steel surfaces.

After 750 hours, first severe erosion marks of the edges were found at the steel shoes (Figure 5b), which could mean later increased leakage and lower efficiency of the pump. However, since such high wear rates were suppressed in the later stages, the edge damages did not progress and the leakage did not increase throughout the tests, which was true also for the DLC-coated system, Figure 7. Most probably, a debris-filter that was used in the testing system removed the dangerous steel wear debris generated in the conventional system. The leakage in both systems was small, but it can be noticed that it was more stable and lower in DLC-coated system than in the conventional one, which could also be a consequence of absence of any wear damage at the DLC-coated shoe surfaces.

Lower amount of wear in DLC-coated system (Figure 3) also suggest lower »pollution« of the oil due to released wear debris. Moreover, since wear particles in the oil also increase the rate of oil oxidation, this could suggest improved oxidation performance of the oil, too. In accordance with this suggestion, we have indeed observed that slightly - but consistently, the oil-oxidation related data, i.e. TAN and viscosity, were always better for oils using the DLC-coated shoes than conventional ones, see Figures 8 and 9. Nevertheless, the TAN and kinematic viscosity results, which indicate the rate of oxidation of the oil did not change intensively, but slowly and steadily, and especially, did not increase abruptly, which would indicate a catastrophic degradation of the oil in the tested period of 2000 hours. The reason for the oil viscosity decrease (Figure 8) in initial stage (before the first 500 hours) is due to molecule rearrangement, however, the subsequent decrease is not obvious and due to low difference of about 1-2 mm^2/s it is believed that it was most probably a result of measurement inaccuracy due to a long testing period. According to TAN data, the oils oxidation occurred to some extent, but this was obviously not at a remarkable level and despite better result for DLC-coated system, the reason for the actual difference cannot be reliably attributed to DLC coating at the surfaces.

5. CONCLUSIONS

- The performance of the hydraulic system with the axial piston pump having DLC-coated piston shoes and use of biodegradable synthetic hydraulic oil was satisfactory in the period of 2000 testing hours operating at 180 bar and 80-85^{o}C of oil temperature.
- The modified pump with the DLC-coated shoes performed better than conventional commercial pump with steel shoes in terms of wear, especially during running-in, thus resulted in lower wear debris generation and only mild polishing wear, with no abrasive or erosive wear at the surfaces, which were observed at the steel shoe surfaces. Nevertheless, both systems performed quite satisfactory throughout the test.
- Oil from the system having DLC-coated surfaces provided slightly – but consistently better TAN and viscosity results. However, the differences were small and can not be reliably and non-disputably attributed to the presence of DLC coating at the surfaces.
- The severe oxidation of the oil did not occurred during 2000 hours in either system.

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