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COMPARATIVE EVALUATION OF WEAR BEHAVIOR OF TRIBO-PAIRS IN RECIPROCATING PUMPS WITH MULTIPLE MATERIALS UNDER DIFFERENT CONDITIONS

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In the study of wear behavior of tribo-pairs in reciprocating pumps, the tribo-pairs can be considered as contact pairs consisting of a disc and pin. In this paper, pin-on-disc wear tests were carried out by using two types of cast iron pin specimens with different materials. Additionally, the effects of the lubrication condition, test load, diamond-like carbon (DLC) coating and plateau honing cross-hatch pattern on wear behavior of the tribo-pairs were investigated. Experimental results based on surface topography analysis and scanning electron micrograph (SEM) analysis show that the lubricant and DLC coating have a positive effect on wear resistance of test specimens. Disc specimens of three material types (i.e. ISO 185/JL/250, tin-bronze, zirconia) are able to show good anti-wear behavior. The tribo-pairs composed of spheroidal graphite cast irons as well as implementation of the plateau honing cross hatch on disc specimens have no significant effect on the wear resistance. The Archard model was used to estimate abrasive wear under dry conditions, which was over-predicted compared to the experimental results.

Keywords: reciprocating pump, tribo-pairs, cast iron pin, wear behavior, wear resistance

1. Introduction

Tribo-pairs in reciprocating pumps consist of crossheads and crosshead bushings, which are often subjected to reverse loads during normal service operation (Li *et al.*, 2021). A potential failure of tribo-pairs is usually associated with destructive debris produced by wear. Due to fragility of the crosshead, it is critical to use compatible materials for the crossheads and crosshead bushings to improve wear resistance. It is therefore important and necessary to understand and be able to predict wear behavior of high-speed tribo-pairs of reciprocating pumps (Miller, 1987). Several standard test methods are available for measuring the friction coefficient and wear performance of tribo-pairs, such as ASTM D6425 and DIN 51834 (ASTM, 2010; Woydt and Ebrecht, 2003).

Cast iron is widely used in the manufacturing of many reciprocating pump parts, such as crankshaft case, crossheads, crosshead bushings, etc. Numerous studies have been carried out on the wear behavior of different cast irons. Mohamadzadeh *et al.* (2009) reported on sliding wear behavior of a gray cast iron surface remelted by tungsten inert gas. Saeidi *et al.* (2016) studied the effect of laser surface texturing on friction behavior and lifetime of grey cast iron reciprocating under starved lubrication conditions. Through development of fractional factorial design, five geometrical texture parameters (feature depth, diameter, length, area fraction and sliding direction) were studied using a design of experiments (DoE), and the reciprocal sliding tests were carried out for a cast iron-steel tribo-pair at a pressure of 24 MPa and a frequency of 6 Hz. Ausserer *et al.* (2016) investigated the influence of various industrially used gases (Ar, N_2, CO_2 and air) on tribological behavior of steel-steel contacts. Cabanettes *et al.* (2015) proposed to map variations in roughness of a cylinder liner by using confocal 3D measuring equipment, and computed tailor made parameters extracting honing texture information. Khanlari *et al.* (2018) conducted a series of ball (WC)-on-plate reciprocating sliding wear tests under moderate and extreme sliding induced stress conditions to illustrate how 58Ni39Ti-3Hf responds as compared to 60NiTi. In addition, to fully understand the reasons causing divergence in the wear response of both materials, they investigated and compared mechanical and micro-tribological properties of these two alloys by means of indentation, hardness and scratch tests. Carrera-Espinoza *et al.* (2016) evaluated tribological properties at the surface of borided and unborided steel employing the ball-on-flat method with sliding reciprocating wear tests, using an Al2O3 ball as the counterpart. In addition, they evaluated coefficients of friction (CoFs) on the boride layers from sliding reciprocating wear tests for dry and lubricated conditions. Ayyagari *et al.* (2018) evaluated reciprocating sliding wear behavior of two high entropy alloys, CoCrFeMnNi and Al0.1CoCrFeNi, in dry and marine environments. Onuoha *et al.* (2016) evaluated sliding wear resistance of TiC cermets in a reciprocating motion using a WC-Co counter face sphere paired against the TiC cermets. Kim *et al.* (2018) compared lubricity of sliding cylinder liner surfaces under different plateau honing marks by friction and wear tests with reciprocating motion. Balarini *et al.* (2020) investigated the influence of both reciprocating and unidirectional rotating tribotests on the tribological performance of MoDTC-containing oils. Dang *et al.* (2020) first systematically studied the effect of Mo element concentration on the crystal lattice constant, microhardness and reciprocating dry sliding friction and wear properties of face-centered cubic (FCC) single phase based CoCrFeNiMo high entropy alloys (HEAs). Liu *et al.* (2021) studied tribological behavior of two types of DLC coatings deposited on GCr15 substrates. Okubo *et al.* (2021) investigated tribological properties of DLC network nanostructures in contact with DLC/steel in a formulated engine oil. Many studies (Malburg *et al.*, 1993; Jocsak *et al.*, 2005; Gore *et al.*, 2011) have shown that the plateau honing cross hatch surface finish method can effectively reduce friction and wear. Kim *et al.* (2021) investigated performance and side effects of uneven plateau-honed surfaces, and conducted friction, wear and failure tests to compare the the performance of the plateau-honed surfaces with different levels of roughness and different profiles.

In this paper, the results of pin-on-disc wear tests carried out on two types of cast iron pin specimens (i.e. ISO 1083/JS/600-3, ISO 185/JL/250) and disc specimens made of different materials under dry, lubrication and DLC coating conditions, were presented. Moreover, the effects of lubrication conditions, test loads, DLC coating and plateau honing cross-hatch patterns on wear behavior of tribo-pairs were investigated. The results of the wear tests were determined on the basis of the friction coefficient and wear weight. Surface topography analysis and scanning electron micrograph (SEM) analysis were conducted on the surface of the test disc, which was helpful to reveal the wear mechanism of test specimens.

2. Experiments

The test specimens of pin and disc used in this paper are shown in Fig. 1. The test pin has a diameter of 15 mm and a height of 22 ± 0.05 mm; the test disc has a diameter of 24 mm and a height of 7.85 ± 0.05 mm. The test pin specimens are made of two basic materials, namely spheroidal graphite cast iron (ISO 1083/JS/600-3) and grey cast iron (ISO 185/JL/250). Some ISO 1083/JS/600-3 test pin specimens were deposited by DLC coating. Six materials were used for test specimens of disc, namely ISO 1083/JS/400-18, ISO 1083/JS/500-10, ISO 185/JL/250, grey cast iron (L161), tin-bronze and zirconia. The material properties of L161, tin-bronze, zirconia are shown in Table 1.

Fig. 1. Test specimens of pin and disc

Table 1. Material properties of L161, tin-bronze, zirconia [wt%]

Materials	L161	Tin-bronze	Materials	Zirconia
C	2.9-3.7	–	CaO	0.0074
Si	1.8-2.6	0.005	MgO	0.0096
Mn	0.5-1.0	–	K_2O	0.00058
P	0.1-0.4	1.5	Na_2O	0.0011
S	< 0.12	0.08	Fe_2O_3	0.0052
Cr	0.1-0.4	–	SiO_2	0.36
Cu	0.3-0.5	81.0-85.0	Al_2O_3	0.75
B	0.03-0.08	–	TiO_2	0.014
Sn	–	6.3-7.5	ZrO_2	92.54
Pb	–	6.0-8.0	Y_2O_3	5.84
Zn	–	2.0-4.0		
Al	–	0.005		

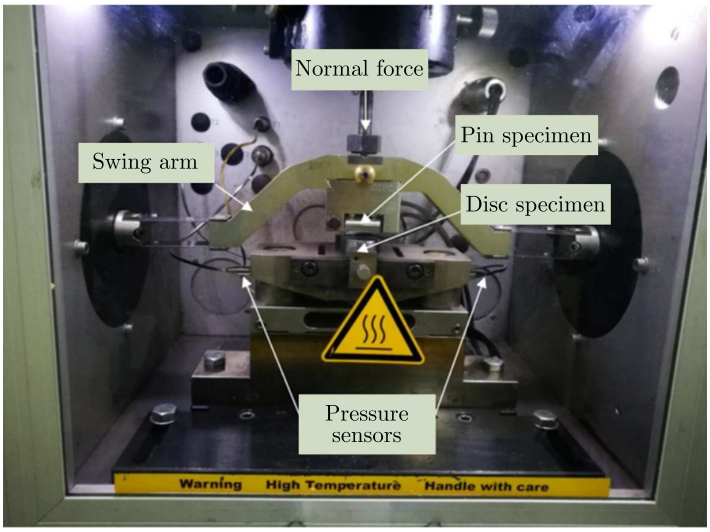
The DLC coating was deposited on the test disc using a non-equilibrium magnetron sputtering process, including two layers of Cr/WC on the bottom and TAC on the top. The L161 test disc was made using a complete liner whose inner surface was plateau honed in a 45° cross-hatch pattern. The test disc specimen and its position in the complete liner are shown in Fig. 2. The unhoned surface of the pieces cut from the complete liner was machined flat to assist in the installation of the test disc.

The SRV® IV test apparatus was used in this study. Figure 3 shows the test chamber of the SRV® IV test apparatus. The apparatus consists mainly of the upper specimen holder, lower specimen holder, swing arm and the pressure sensor. The upper and lower specimen holders are designed to accommodate the pin and disc specimens, respectively. The swing arm is used for providing vibratory movements of the pin specimens. The pressure sensors are used to interpret the test data. The constant test parameters, i.e., a frequency of 50 Hz, temperature of 50°C, stroke of 1 mm, test duration of 1 h, were applied to the wear test.

Three groups of wear tests were designed and performed under ISO-VG 220 lubricant and dry conditions with test loads of 30 N and 100 N, respectively. The first group of tests was designed for investigating the effect of DLC coatings on friction and wear behavior for the ISO 1083/JS/600-3 test pin specimens sliding against ISO 1083/JS/400-18 and ISO 185/JL/250 test

Fig. 2. Representation of L161 disc specimens made from the complete liner

(a)



(b)

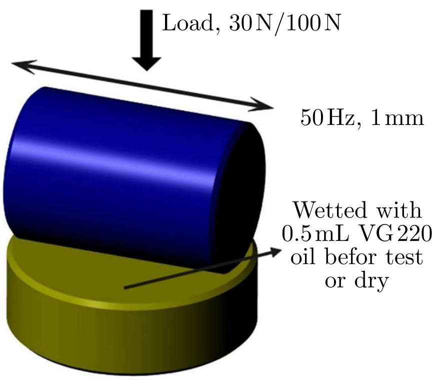


Fig. 3. (a) Test chamber of the SRV® IV test apparatus, (b) schematic representation of the pin-on-disc test specimens

disc specimens. The second and third groups of tests were designed for studying friction and wear behavoir for the ISO 1083/JS/600-3 and ISO 185/JL/250 test pin specimens sliding against different materials, which aims at distinguishing the more suitable tribo-pairs in reciporcating pumps.

3. Results and analysis

3.1. Test results of the friction coefficient and wear weight

Figure 4 shows the typical result for variation in friction coefficients of the ISO 185/JL/250 sliding against ISO 185/JL/250. An electronic balance with accuracy of 0.01 mg was used to measure wear weight of the test discs. The wear rate $W+s$ [mm^3/Nm] of materials, as proposed by previous studies (Zhang *et al.*, 2015; Yin *et al.*, 2021), is given by

$$W_s = \frac{\Delta m}{\rho N L} \tag{3.1}$$

where ρ is density of the worn material, N is the normal load, L is the total sliding distance, and Δm is the wear weight.

Table 2 summarises the test results expressed by the friction coefficient of all specimens and the wear weight and wear rates of the test discs. As can be seen from Table 2, the friction

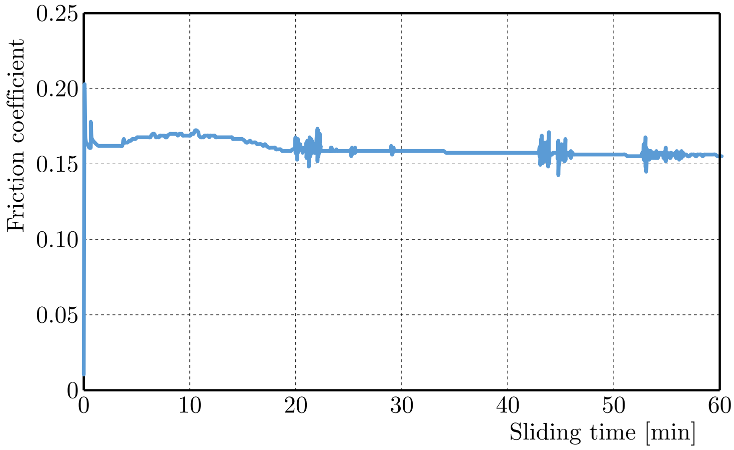


Fig. 4. Variation in friction coefficients of the ISO 185/JL/250 sliding against ISO 185/JL/250

Table 2. Test conditions and test results

Test gr.	Pin specimen	Disc specimen	Lubri-cation	Normal force [N]	COF	Wear weight [mg]	W_s [10^{-6} mm^3/Nm]
1	ISO 1083/JS/600-3	ISO 1083/JS/400-18	Dry	30	1.088	2.88	37.558
		ISO 185/JL/250	Dry	30	1.023	3.98	54.194
	ISO 1083/JS/600-3 with DLC coating	ISO 1083/JS/400-18	Dry	30	0.567	1.78	23.213
		ISO 485/JL/250	Dry	30	0.496	2.08	28.322
	ISO 1083/JS/600-3 with DLC coating	ISO 1083/JS/400-18	Dry	100	0.678	14.7	57.512
		ISO 185/JL/250	Dry	100	0.601	3.12	12.745
2	ISO 1083/JS/600-3	ISO 1083/JS/400-18	VG 220	100	0.175	0.11	0.430
		ISO 185/JL/250	VG 220	100	0.16	0.19	0.776
		ISO 1083/JS/500-10	VG 220	100	0.166	0.26	1.017
		L161	VG 220	100	0.157	0.59	2.410
		Tin-bronze	VG 220	100	0.167	0	0
		Zirconia	VG 220	100	0.155	0.04	0.190
3	ISO 185/JL/250	ISO 185/JL/250	VG 220	100	0.163	0.37	1.511
		L161	VG 220	100	0.164	0.38	1.552
		Tin-bronze	VG 220	100	0.163	0	0
		Zirconia	VG 220	100	0.164	0.08	0.380

coefficients of ISO 1083/JS/600-3 test pins with DLC coating and without DLC coating vary from 0.496 to 1.088 under the dry condition, and the friction coefficients for both ISO 1083/JS/600-3 and ISO 185/JL/250 test pins sliding against different test discs are almost the same, i.e. by a value of 0.16 under the lubrication condition. For the lubraication condition, the smallest wear rates are obtained for the tin-bronze and zirconia test discs sliding aginst both the ISO 1083/JS/600-3 and ISO 185/JL/250 test pins.

3.2. Test results of the surface profile

In order to investigate the effect of the DLC coating and lubrication conditions on wear of the test discs, the surface profile of the specimens was analyzed in detail using the white light interferometry method. This method can measure the rough surface profile of an object, as shown in Figs. 5 and 6, which are the surface profiles of ISO 185/JL/250 and ISO 1083/JS/400--18 test disc specimens under different working conditions. Figure 5a shows the surface profile of an ISO 185/JL/250 test disc specimen tested with an ISO 1083/JS/600-3 test pin specimen

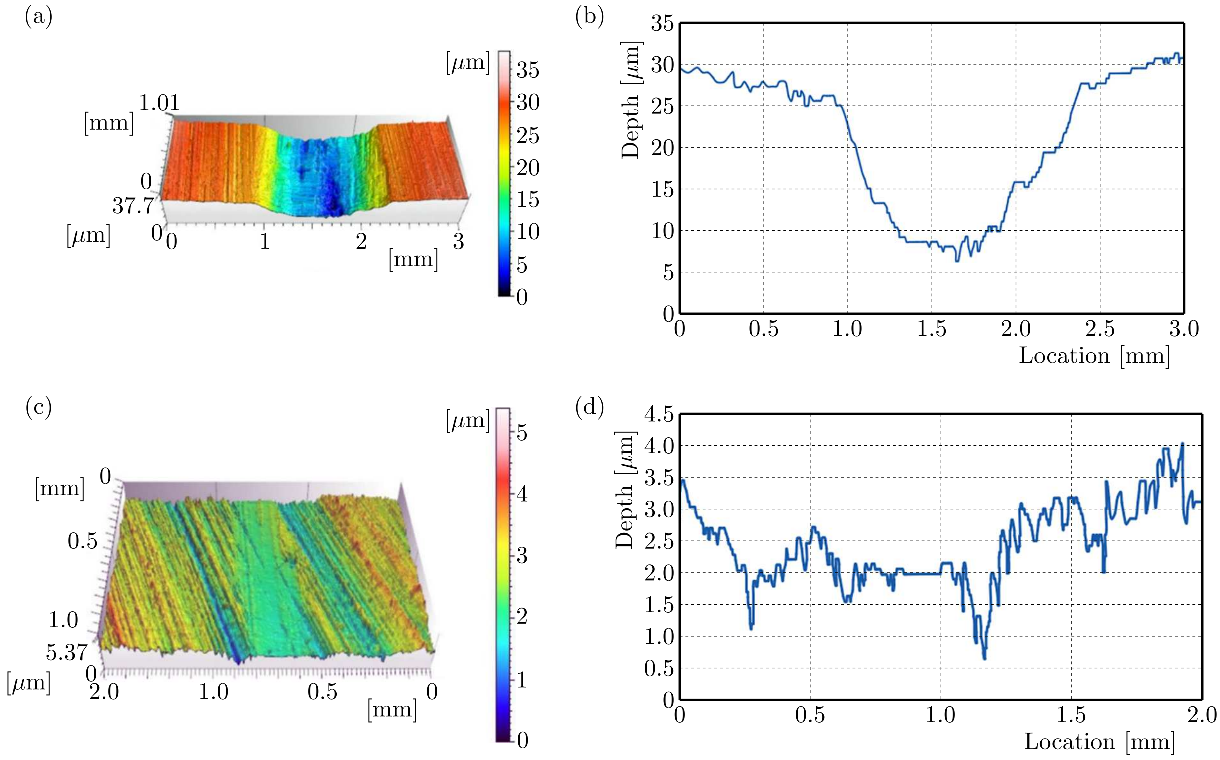


Fig. 5. The profiles of ISO 185/JL/250 test discs under different conditions: (a) 3D profile under dry condition, (b) 2D profile in depth under dry condition, (c) 3D profile under lubrication condition, (d) 2D profile in depth under lubrication condition

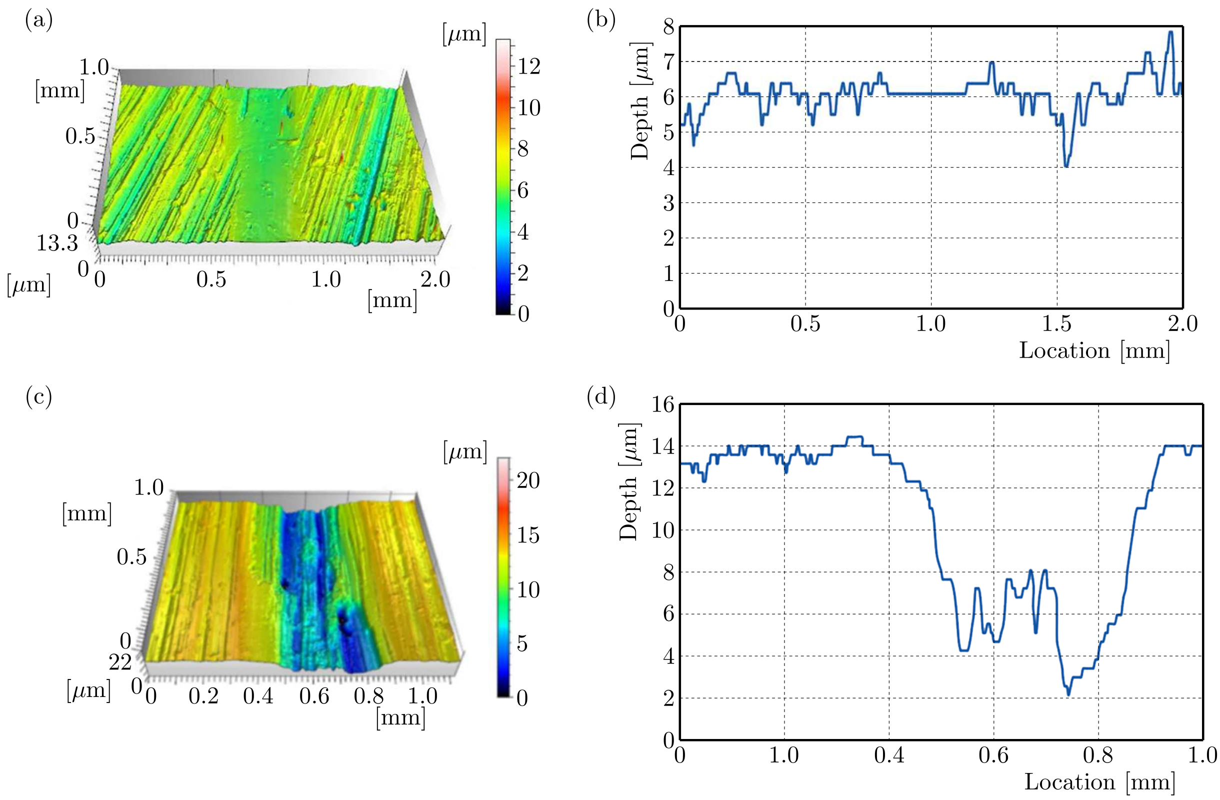


Fig. 6. The profiles of ISO 1083/JS/400-18 test discs under different condition: (a) 3D profile of the ISO 1083/JS/400-18 test disc tested with the ISO 1083/JS/600-3 test pin with DLC coating, (b) 2D profile in depth of the ISO 1083/JS/400-18 test disc tested with the ISO 1083/JS/600-3 test pin with DLC coating, (c) 3D profile of the ISO 1083/JS/400-18 test disc tested with the ISO 1083/JS/600-3 test pin without DLC coating, (d) 2D profile of the ISO 1083/JS/400-18 test disc tested with the ISO 1083/JS/600-3 test pin without DLC coating

under the unlubricated condition and a test load of 30 N. Figure 5b shows the corresponding 2D profile curve, Fig. 5c shows the surface profile of an ISO 185/JL/250 test disc specimen tested with an ISO 1083/JS/600-3 test pin specimen under the condition of lubrication and a test load of 100 N, Fig. 5d shows the corresponding 2D profile curve. As can be seen from the 2D profile curve (Fig. 5b), the wear depth in the x-coordinate direction is approximately 23 μm for unlubricated conditions. Comparing the 2D profile curves ((b) and (d)) under the two working conditions, it can be seen that the surface profile of the test area of the ISO 185/JL/250 test disc is relatively flat under lubrication conditions despite the increased test load, which indicates that the introduction of lubrication has a significant impact on roughness of the ISO 185/JL/250 test disc. Figures 6a-6d show the surface profile of ISO 1083/JS/400-18 test disc specimens tested using two types of ISO 1083/JS/600-3 test pin specimens (with and without DLC coating) with lubrication and a test load of 100 N. As can be seen from the 2D profile curve (Fig. 6b), the wear depth in the x-coordinate direction is approximately 11 μm. The surface of the ISO 1083/JS/400-18 test disc tested with ISO 1083/JS/600-3 test pin specimens with DLC coating shows good wear resistance.

3.3. Wear surface morphology analysis

Figure 7 shows SEM photographs of the wear scar of test disc specimens tested with the ISO 1083/JS/600-3 test pin under different conditions. It can be seen from Fig. 7a that severe

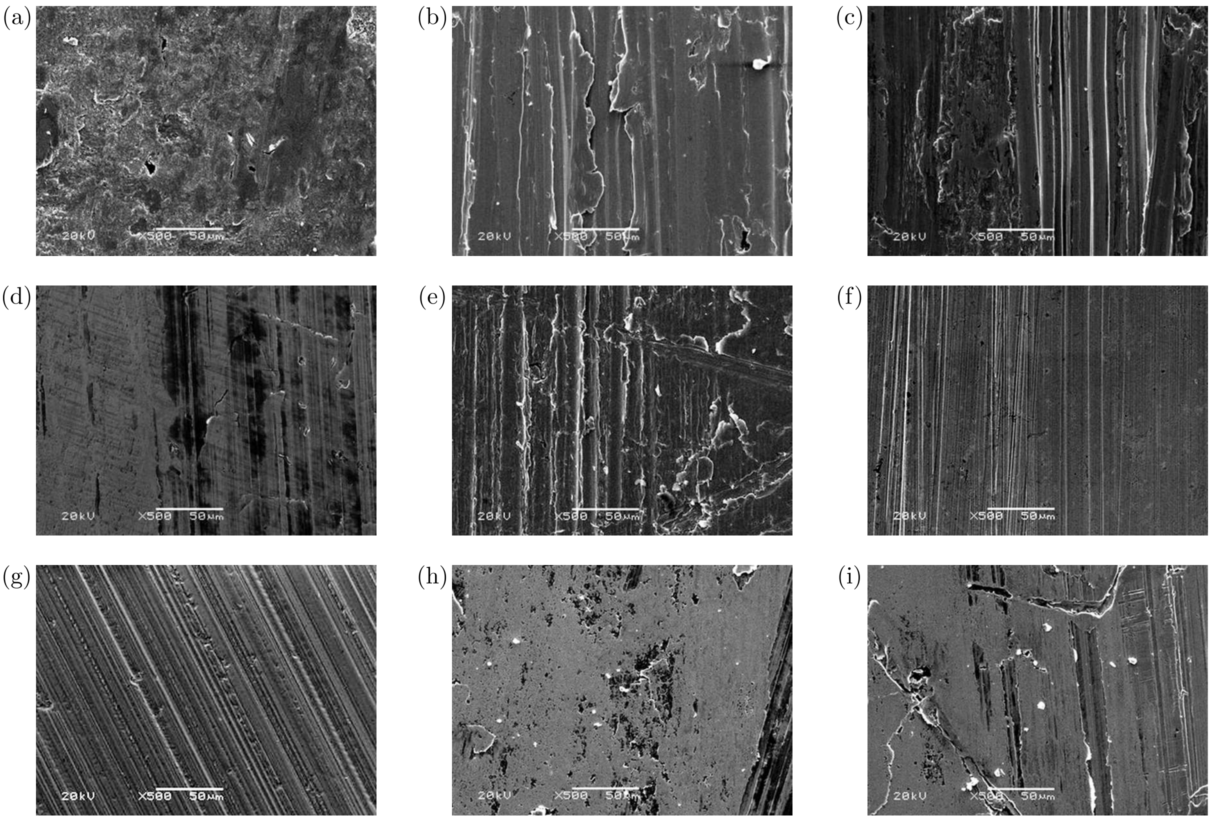


Fig. 7. SEM morphology of test disc specimens: (a) ISO 1083/JS/400-18 test disc, (b) ISO 1083/JS/400-18 test disc, (c) ISO 1083/JS/500-10 test disc, (d) ISO 185/JL/250 test disc, (e) L161 test disc, (f) tin-bronze test disc, (g) zirconia test disc, (h) ISO 1083/JS/400-18 test disc tested with test pin specimens with DLC coating, (i) ISO 185/JL/250 test disc tested with test pin specimens with DLC coating

adhesive wear occurs on the ISO 1083/JS/400-18 test disc under dry conditions. Compared with that, the wear degree of the ISO 1083/JS/400-18 test disc is alleviated due to the introduction of lubrication, as shown in Fig. 7b. The wear behavior of the ISO 1083/JS/500-10 test disc under lubrication condition is shown in Fig. 7c. It can be seen from Fig. 7c that the delaminated areas are associated with the abrasive grooves and microcracks formed on the contoured surface of the ISO 1083/JS/500-10 test disc. In Fig. 7d, it is observed that the ISO 185/JL/250 test disc shows good wear resistance. Abrasive grooves can be clearly seen on L161 test disc in Fig. 7e, similar to the results shown in Fig. 7b,c. As shown in Fig. 7f,g, it is observed that there are shallow furrow scratches on the surface of the tin-bronze test disc, while the zirconia test disc has good wear resistance. Figures 7h,i show the effect of test pin specimens with DLC coating on the sliding wear performance of the ISO 1083/JS/400-18 and ISO 185/JL/250 test discs. It is found that for the ISO 1083/JS/400-18 test discs, the wear resistance can be improved by using DLC coating on the end face of the test pin. However, the introduction of DLC coating on the back of the test pin has no significant effect on the ISO 185/JL/250 test disc.

Figure 7 shows SEM photographs of the test disc specimens tested with the ISO 185/JL/250 test pin, and SEM photographs of the test disc specimens made of various materials under the test load of 100 N and lubrication conditions. Similar to the results shown in Fig. 7i, the ISO 185/JL/250 test disc has good wear resistance as shown in Fig. 8a. It can be seen form Fig. 8b, the wear degree of L161 test disc is relatively weak compared with the wear results of the test disc tested with the ISO 1083/JS/600-3 test pin (Fig. 7e). The wear behavior of the tin bronze and zirconia test discs is consistent with the wear results of the wear test using the ISO 1083/JS/600-3 test pin, as shown in Fig. 7d.

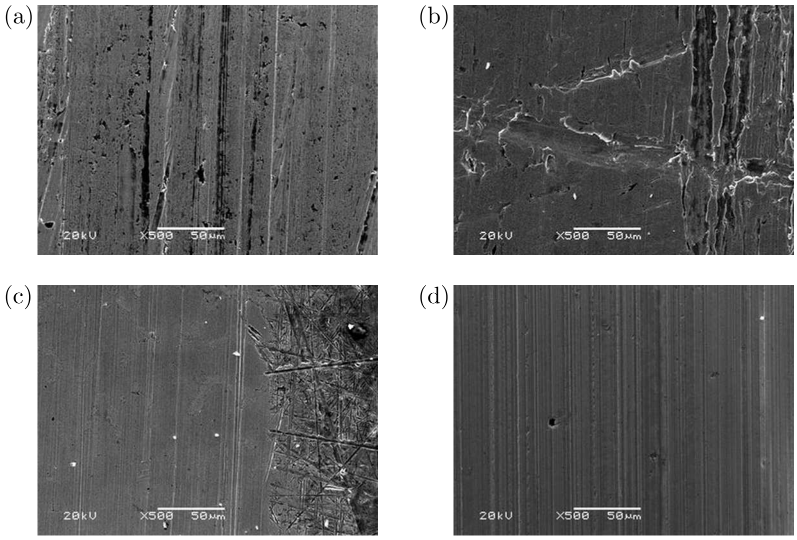


Fig. 8. SEM morphology of test disc specimens: (a) ISO 185/JL/250 disc, (b) L161 disc, (c) tin-bronze, (d) zirconia disc

4. Discussion

4.1. Influence of lubrication

The friction coefficient of tribo-pairs of the ISO 1083/JS/600-3 test pin and ISO 185/JL/250 test disc and the ISO 1083/JS/600-3 test pin and ISO 1083/JS/400-18 test disc under unlubricated conditions (test load of 30 N) is approximately 5 times higher than that under lubrication conditions (test load of 100 N).

The well-know adhesive wear model proposed by Archard is shown as

$$V_c = K\frac{LS}{H} \tag{4.1}$$

where V_c is the volume wear per unit sliding stroke, L is the load, H is the hardness, S is the sliding stroke, and K is the abrasive wear coefficient. The abrasive wear coefficient of a cast iron/cast iron pair under dry conditions is approximately $9.9 \cdot 10^{-4}$ (Rajkumar and Aravindan, 2013).

The hardness H and density ρ of the ISO 185/JL/250 test disc are 180 HV and 7.0 g/cm^3, respectively. Therefore, the wear weight of the ISO 185/JL/250 test disc can be calculated as the product of the volume wear per unit sliding stroke V_c, frequency f, test duration t and density ρ, which is in a value of 208 mg. The result obtained based on the Archard model overpredicts the adhesive wear, which may be due to the estimation of the abrasive wear coefficient K of the tribo-pairs of the 1083/JS/600-3 test pin and ISO 185/JL/250 test disc.

4.2. Material selection of crosshead liners

It is very important to select appropriate materials for crosshead liners, which can minimize wear caused by reciprocating motion of the crosshead in a reciprocating pump. As shown in Section 3, for ISO 1083/JS/600-3 and ISO 185/JL/250 test pin specimens, test disc specimens made of ISO 185/JL/250, tin-bronze, zirconia materials have good wear resistance. The test results suggest that the ISO 185/JL/250, tin-bronze, zirconia discs may be more suitable considering raw materials of the crosshead liner in a reciprocating pump.

4.3. Influence of DLC coating and plateau honing

Under the test load of 100 N and lubrication conditions, the friction coefficient between the ISO 1083/JS/500-10 and ISO 185/JL/250 test disc and the ISO 1083/JS/600-3 test pin end face is very similar to that between the ISO 1083/JS/500-10 and ISO 185/JL/250 test disc and test pin without DLC coating. Under dry conditions, the DLC coating method using the test load of 100 N shows good wear resistance in terms of the friction coefficient and wear weight compared with the results of the ISO 1083/JS/600-3 test pin without DLC coating using the test load of 30 N. The effect of the plateau honing method on wear resistance is not significant. For L161 test disc, the surface should be matched to ISO 1083/JS/600-3 and ISO 185/JL/250 test pins. Zhang *et al.* (2015) reported that the plateau honing method resulted in higher steady-state friction levels compared to other surface finish methods, which might relate to the intersection angle, surface roughness and lubrication conditions.

5. Conclusions

In this study, in order to explore wear behavior of tribo-pairs in a reciprocating pump, pin-on-disc wear tests under dry, lubrication conditions and DLC coating were carried out. The conclusions are as follows:

- The presence of a lubricant has a significant effect on wear behavior of tested specimens. The friction coefficients under a normal load of 30 N under dry conditions are approximately 5 times higher than those under a normal load of 100 N in VG 220 lubricated conditions.
- The tribo-pairs consisting of spheroidal graphite cast iron materials are most likely to cause abrasive wear. Test disc specimens made of ISO 185/JL/250, tin-bronze and zirconia show good wear resistance against two cast iron test pin specimens, which indicates the capability to be used as the linear raw material for crossheads.
- The DLC coating can improve tribological behavior of test pin substrate materials under lubricated sliding conditions. However, the plateau honing approach has little effect on the wear resistance of the tested disc specimens.

Acknowledgment

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