

Failure Analysis and Countermeasures of Crosshead-Cylinder Hole Tribo-Pair in a Reciprocating Plunger Pump

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1. Introduction

Reciprocating pumps are widely used in petroleum, gas, and coal mining pumping applications [1]. Crossheads are essential components in reciprocating pumps or compressors that connect the swinging connecting rod and reciprocating piston rod in hinge form to transmit the connecting rod force [2, 3]. Practically, the majority of problems associated with reciprocating pumps or compressors are caused by or associated with crosshead failures. Therefore, understanding and predicting the wear behavior of high-speed crosshead-cylinder hole tribo-pairs in reciprocating pumps or compressors is important [3].

Many studies have been conducted on the dynamic characteristics and failure mechanisms of crosshead-cylinder hole tribo-pairs. Yuan et al. [4] performed three-dimensional finite element analyses to evaluate the fatigue life of the crosshead in a plunger pump. Huang et al. [5] developed an oil temperature-rise model between the sliding shoe and guiding plates of 6000 HP fracturing pump and performed test validations. Ropyak et al. [6] proposed an engineering model for analyzing the “crosshead-slide rail” wear effect on the stress state of a double piston pump’s rod. Xiao et al. [7] studied the failure mechanism related to clearance faults between the linkage and crosshead of a reciprocating compressor by establishing ADAMS simulation and kinematic mechanism models. Pu et al. [8] proposed different methods for the surface strengthening of crossheads and sliding sleeves for a drilling pump to improve the anti-wear characteristics and extend the tribo-pairs’ service life.

In this study, the failure of the crosshead-cylinder hole tribo-pairs in a reciprocating pump was investigated. The crank-connecting rod-crosshead mechanism was analyzed to obtain the instantaneous velocity of the crosshead. The reason for the failure of the crosshead-cylinder hole tribo-pairs was investigated using macroscopic observations, scanning electron microscopy (SEM), material properties and roughness analyses, energy dispersive spectrometry (EDS), and lubricating oil quality analysis. An oil supply system investigation was designed and tested. A comparative study on the effect of surface roughness on anti-wear behavior in terms of pin-on-disc wear tests was performed.

2. Crank-Connecting Rod-Crosshead Mechanism

Fig. 1 shows a schematic of the crosshead motion driven by a crankshaft. Here, O is the rotating center of the crankshaft ratio, C is the movement center of the crosshead, and A and B are the top dead center (TDC) and bottom dead center (TDC) of the crosshead, respectively. |OD| is equal to the eccentricity of the crankshaft r , and |DC| is equal to the center spacing of the connecting rod l .

$$v = -r\omega \left(\sin\phi + \frac{\lambda}{2} \sin 2\phi \right), \quad (1)$$

where r is the crank radius, ω is the angular velocity, λ is the ratio of the connecting rod length l to the crank radius r , and ϕ is the transmission angle. The reciprocating pump parameters are listed in Table 1.

The instantaneous velocity of the crosshead can be calculated using Eq. (1), which is illustrated in Fig. 2. It can be observed that the maximum velocity at the top and bottom dead centers are 2.47 m/s and -2.47 m/s, respectively.

The following main observations can be made: the primary wear modes of the crossheads and cylinder holes were scratches and adhesion. The primary locations of the

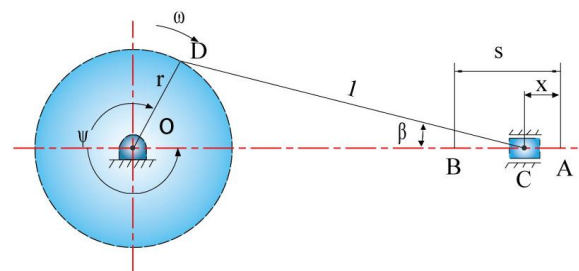


Fig. 1 Schematic of a crosshead motion driven by a crankshaft

Table 1

Parameters of the reciprocating pump	
Parameter	Value
r	35 mm
ω	69.5 rad/s
l	220 mm
λ	0.159

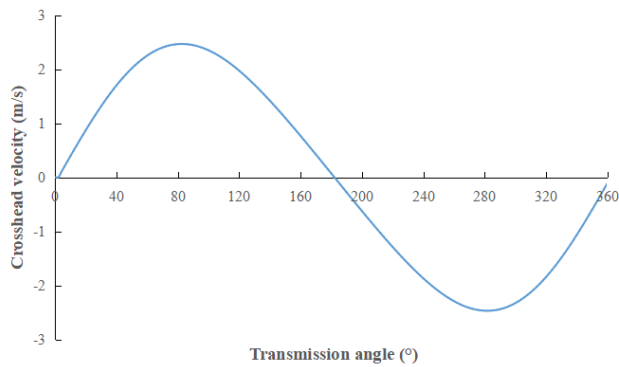


Fig. 2 Simultaneous velocity of the crosshead during operation

3. Experimental Failure Analysis and Results

3.1. Macroscopic observation

A quintuple reciprocating pump was used to provide a high-pressure emulsion medium to hydraulic supports in an underground coal mine with a rated flow rate of 630 L/min and rated pressure of 35 MPa. The operating time of this reciprocating pump was less than one year. An abnormally high lubricating oil temperature was detected, and a large amount of metal debris was found in the oil filter. The pump was then transported to the ground and disassembled. It was found that all five crossheads and cylinder holes of the reciprocating pump were significantly scuffed, as shown in Fig. 3.

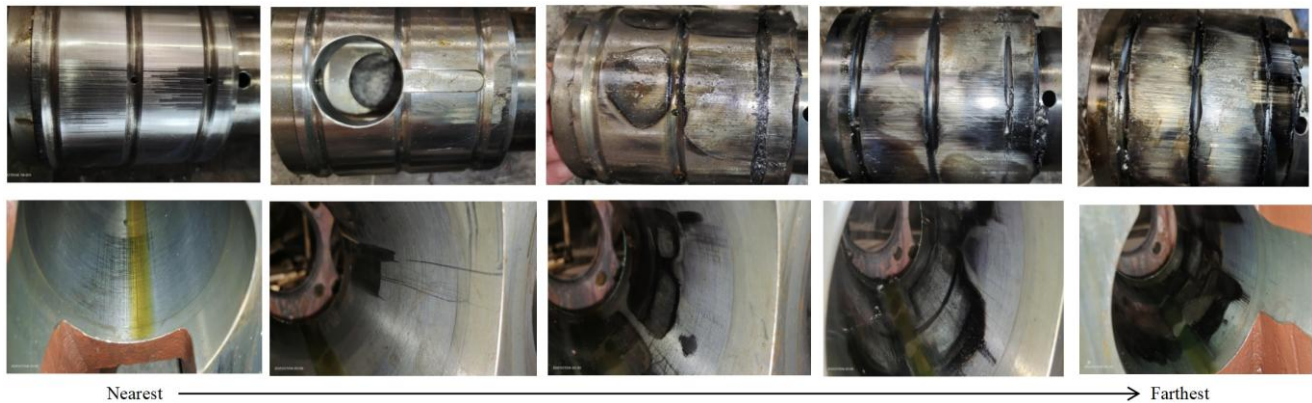


Fig. 3 Five crossheads and skidways from the position near to the motor and the position near to the oil pump

scratches and adhesion were the bottom and/or both sides of the crossheads and cylinder holes. More severe scratches and adhesion were observed as cylinder hole approaches the injection oil pump.

3.2. Material properties and roughness analyses

The material properties and chemical compositions of the as-received crosshead and crankcase (including the cylinder holes) were determined, as listed in Tables 2 and 3. The roughness of the crosshead and cylinder hole could only be measured for the new parts because of the severe wear of the as-received tribo-pairs. The arithmetic mean roughness R_a of the new crosshead was measured using a Marsurf XR20 optical profiler, as shown in Fig. 4, a, and was found to be $0.40 \pm 0.26 \mu\text{m}$. The arithmetic mean roughness R_a of the new cylinder hole was measured using a Marsurf M300C optical profiler, resulting in a value of $0.97 \pm 0.78 \mu\text{m}$, as shown in Fig. 4, b.

Table 2

Material properties of the crosshead and crankcase

Material properties	Crosshead	Crankcase (cylinder hole)
Tensile strength, MPa	513.61	567.77
Yield strength, MPa	474	504.22
Elongation, %	0.8	16.9
Brinell hardness, HBW	247	150–155
Reduction of area, %	0.2	20.8
Main Phase	Ferrite	Ferrite

3.3. SEM morphology and EDS analyses

Two pieces were cut from different positions of the as-received crosshead with different wear forms, that is abrasive and adhesive wear, as shown in Fig. 5. SEM and EDS analyses were conducted on the two samples. Fig. 6 shows the SEM photographs of the wear scars of the two pieces. Abrasive grooves are clearly observed in Piece #1 in Fig. 6, a and 6, b, and severe adhesive wear occurs in Piece #2, as shown in Fig. 6, c and 6, d. Fig. 7 shows the EDS results obtained for the two samples. Compared with the EDS results for Piece #1 shown in Fig. 7, a, the adhesion in the worn area of Piece #2 contained extra carbon, oxygen, phosphorus, and molybdenum particles, which indicates the formation of an adhesion bond and transfer of portions of the material from the cylinder hole to the crosshead.

Table 3

Chemical compositions of the crosshead and crankcase

Element	Crosshead	Crankcase (cylinder hole)
Al	0.4	
Si	2.89	2.91
P	0.01	0.03
S	0.09	0.19
Cr	0.41	0.05
Mn	0.61	0.3
Cu	0.49	0.06
Mo	0.07	-
Zn	-	0.03
Fe	Bal.	Bal.

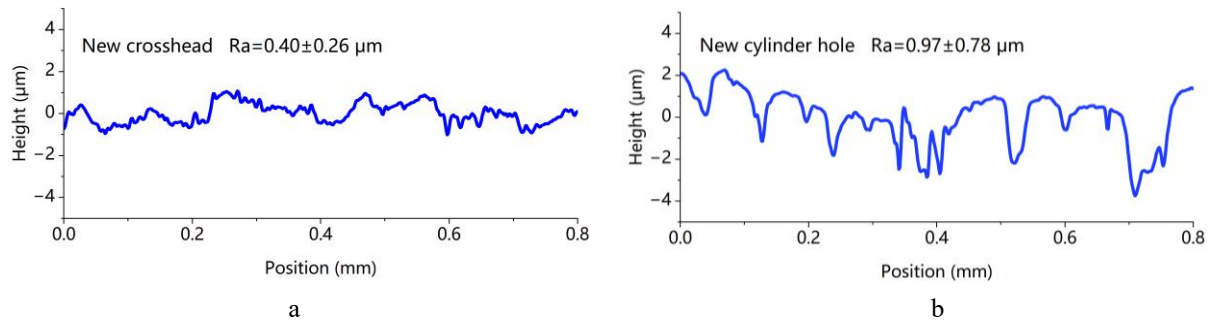


Fig. 4 The tested Ra : a – a new crosshead, b – a new cylinder hole

3.4. Qualitative analysis of lubricating oil

The oil lubricant was changed once based on the maintenance records. A small amount of fresh lubricating oil was collected from a coal mine. The required viscosity class of the lubricating oil was VG220. Table 4 lists a comparison between the oil quality test results and reference values [9-14]. Table 4 indicates that the tested weld point based on the four-ball method [9], which is significantly smaller than the reference value of ≥ 250 kgf. The scar diameters of the three lower balls are shown in Fig. 8. The average scar

diameter obtained from Fig. 8 was approximately 0.456 mm. Oil contamination and degradation monitoring was performed using Fourier transform infrared spectrometry [10], as shown in Fig. 9. The oxidation by-product was clearly detected with an absorbance of 0.013. The anti-wear behavior of the crosshead-cylinder hole tribo-pair is strongly dependent on the load-carrying capability of the lubricating oil film between the crosshead and cylinder hole. Therefore, the failure of the crosshead-cylinder hole tribo-pairs can be attributed to the insufficient kinematic viscosity and weld point of the lubricating oil.



Fig. 5 Two pieces of the as-received crosshead with different wear form

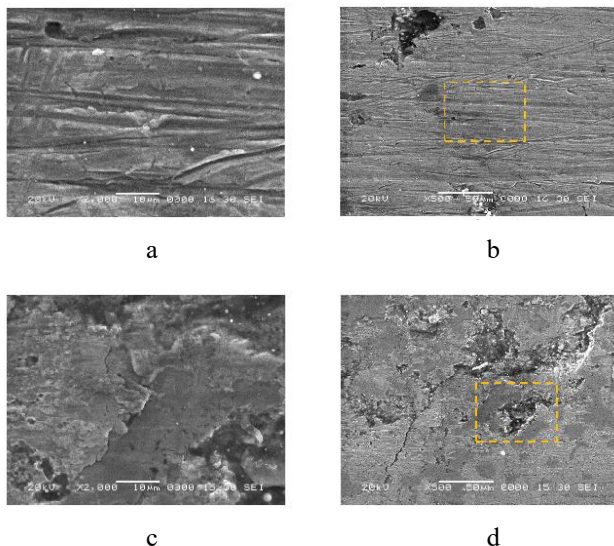
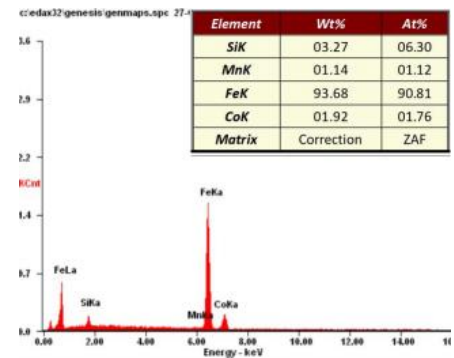
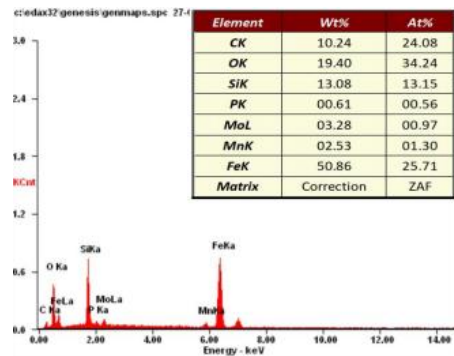


Fig. 6 SEM photographs of the wear scar of the two pieces: a – Piece #1 with a magnification of 2000 times, b – Piece #1 with a magnification of 500 times with the orange box marks the testing area of EDS analysis, c – Piece #2 with a magnification of 2000 times, d – Piece #2 with a magnification of 500 times and the orange box marks the testing area of EDS analysis



a



b

Fig. 7 EDS results of the wear scar of the two pieces: a – Piece #1, b – Piece #2

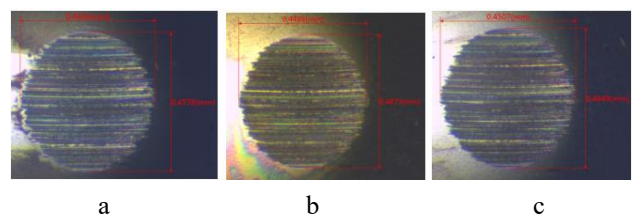


Fig. 8 Scar diameters of three points a, b and c based on Four-ball method

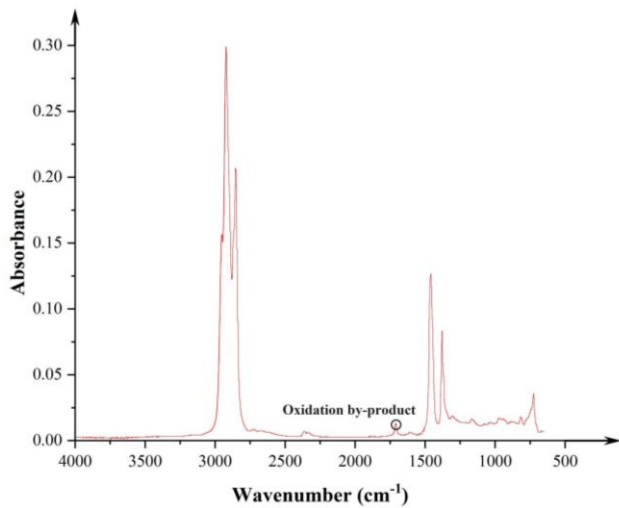


Fig. 9 Fourier Transform Infrared Spectrometry result of the as-received oil

Table 4
Comparison between the tested property of the as-received oil and the reference values

Property	Standard	Test results	Reference values
Kinematic viscosity at 40°C, mm²/s	ISO 3104 (ISO, 2020)	123.5	220
Kinematic viscosity at 100°C, mm²/s	ISO 3104 (ISO, 2020)	11.57	19.4
Viscosity index	ISO 2909 (ISO, 2002)	76	100
Acid number, mgKOH/g	ASTM D664 (ASTM, 2019)	2.923	-
Weld point, kgf	ASTM D2266 (ASTM, 2023)	200	≥250
Scar diameter for Four-ball method, mm	ASTM D4172 (ASTM, 2021)	0.456	-

4. Discussion

4.1. Oil supply investigation

The reliability of the crosshead-cylinder hole tribopair is strongly dependent on the delivery of the lubricant between the crosshead cylinder holes. The original lubrication design (Option A) used an integrated oil pump mounted on the crankshaft of the reciprocating pump with a displacement of 50 mL/rev. To investigate the effect of the lubrication design on the lubricating performance in the cylinder hole of the reciprocating pump, three other lubrication designs were proposed: an integrated oil pump mounted on a crankshaft with a displacement of 60 mL/rev (Option B), a combination of a 50 mL/rev integrated oil pump and 50 mL/rev independent oil pump driven by a 1500 rpm motor (Option C), and combination of a 60 mL/rev integrated oil pump and a 50 mL/rev independent oil pump driven by a 1500 rpm motor (Option D).

The tested total oil flow rate from the oil inlet to the five cylinder holes and the pressures of the oil inlets to cylinder holes 1 and 5, located the closest and the farthest from the integrated oil pump, are shown in Fig. 10. Fig. 11 shows the tested total oil flow rates for the four options. The flow rates at 40 and 60°C for Option C are 19.75 L/min and 27.75 L/min, respectively, which are the largest among

those of the other options. Fig. 12 shows the tested pressures at the nearest and farthest inlets at 40 and 60°C, which also indicates that Option C exhibits the largest input pressure to the five cylinder holes at the two temperature levels. Therefore, Option C should be the optimized oil supply design.

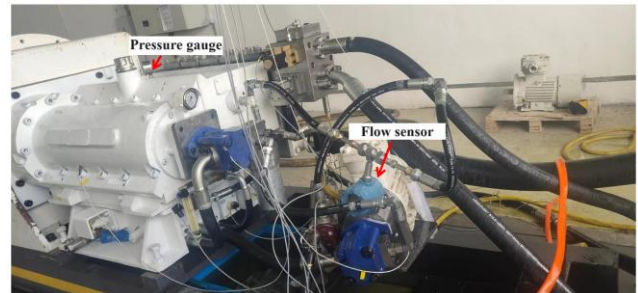


Fig. 10 The tested total oil flow rate and individual pressure for the oil inlet to the five skidways

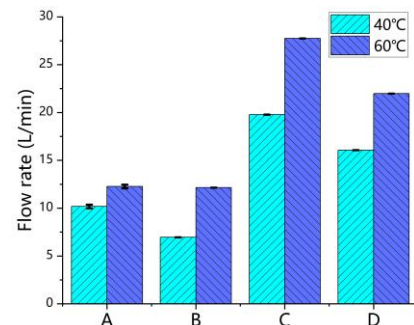


Fig. 11 The tested total oil flow rates for the four options

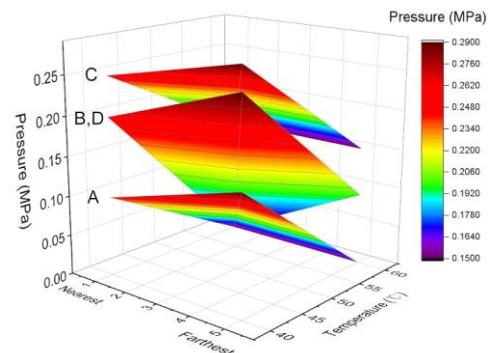


Fig. 12 The tested pressures at the nearest and farthest inlets at 40°C and 60°C

4.2. Effect of surface roughness on the anti-wear behavior of crosshead-cylinder hole tribopair

The surface roughness of the crosshead was ensured by cylindrical grinding. After precision milling, a tumbling treatment was used to improve the surface roughness of the cylindrical hole. Compared to the surface roughness of the crosshead based on the cylindrical grinding process, the surface roughness of the cylinder hole was strongly dependent on the cutting parameters of the combination of precision milling and tumbling treatment, which is likely to lead to an unstable finished surface quality. Therefore, investigating the effect of surface roughness on the anti-wear behavior of crosshead-cylinder hole tribopairs is necessary.

Four groups of pin-on-disk specimens were used to represent the crosshead-cylinder hole tribopairs with different average surface roughness values, in order to investigate

the effect of surface roughness on the anti-wear behaviour of the tribo-pair. The pin specimens, representing the cross-heads, were made from ISO 1083/JS/600-3 and had a diameter of 15 mm and height of 22 mm. The disc specimens, representing the cylinder holes, manufactured according to ISO 1083/JS/400-18, had a diameter of 24.4 mm and height of 7.9 mm. The nominal value of the arithmetic mean roughness R_a of the pin specimens was $0.8 \mu\text{m}$. The nominal values of the arithmetic mean roughness R_a of the disc specimens used in this study were 0.4 , 0.8 , 1.6 , and $2.5 \mu\text{m}$ processed by auto lapping and polishing machine (UNIPOL-1200M) with different types of sandpaper and polishing time, respectively. The contact between the pin and disc specimens was wetted with 0.5 mL Shell VG220 oil before testing.

The pin-on-disc specimens were tested using an SRV IV test apparatus, as shown in Fig. 13. The apparatus consists mainly of the upper specimen holder, lower specimen holder, swing arm and the pressure sensor. 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 normal applied load of 100 N , frequency of 50 Hz , temperature of 50°C , stroke of 1 mm , test duration of 1 h , were applied to the wear test.

Fig. 14 shows the relationship between the friction coefficients and sliding time of the pin specimens sliding against disc specimens with different R_a values. Almost no variation can be observed in the friction coefficients for $R_a = 0.4 \mu\text{m}$. The value of the steady-state friction coefficient for $R_a = 0.4 \mu\text{m}$, that is, approximately 0.14 , is the smallest, compared to those for the other three R_a conditions.

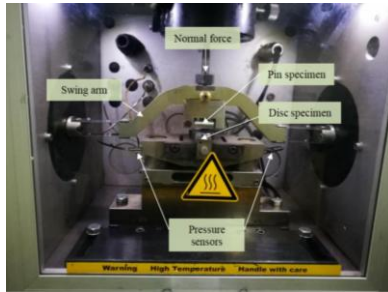


Fig. 13 Test chamber of the SRV IV test apparatus

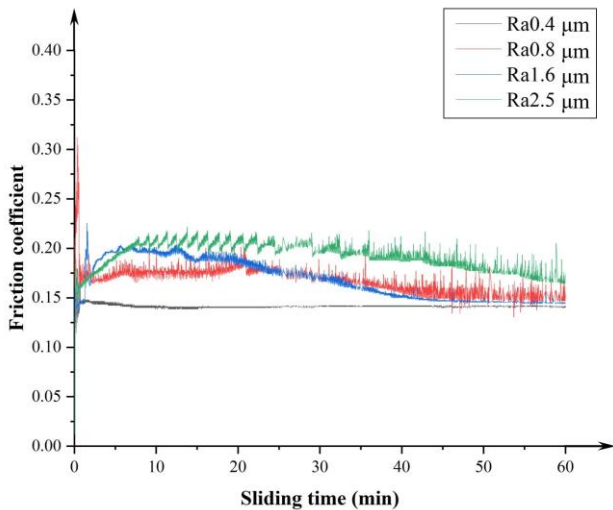


Fig. 14 Friction coefficients of the pin specimens sliding against the disc specimens with different R_a values

The wear rate, W_s (mm^3/Nm), of the materials, as proposed in previous reports [15-16], is given by Eq. (2):

$$W_s = \frac{\Delta m}{\rho N L}, \quad (2)$$

where ρ denotes the density of the worn material; N is the normal load; L is the total sliding distance; and Δm is the wear weight. A weight-analysis method [16] was used to measure the wear weights of the pin and disc specimens. Fig. 15 shows the wear rates of the ISO 1083/JS/600-3 pin specimens sliding against the ISO 1083/JS/400-18 disc specimens with different R_a values. It is shown in Fig. 15 that the wear rates for the pin and disc specimens for the disc specimen under $R_a = 0.4 \mu\text{m}$ condition were significantly smaller than those for the disc specimens under the other three R_a conditions. For the disc specimens at $R_a \geq 0.8 \mu\text{m}$ conditions, the wear rates of the ISO 1083/JS/400-18 disc specimens were larger than those for the ISO 1083/JS/600-3 pin specimens.

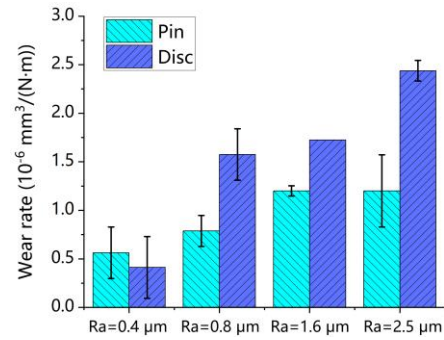


Fig. 15 Wear rates of the pin specimens sliding against the disc specimens with different R_a values

5. Conclusions

The failed crosshead-cylinder hole tribo-pairs in a reciprocating plunger pump with a maximum velocity of 2.47 m/s showed the obvious abrasive and adhesive wear modes, and there was a transfer of portions of the material from the cylinder hole to the crosshead. Based on the qualitative analysis of lubricating oil, the likely reason for severe wear of the crosshead-cylinder hole tribo-pairs should be contributed to the insufficient kinematic viscosity and weld point of the lubricating oil. Then, improvements of the tribological behavior of the crosshead-cylinder hole tribo-pair including oil supply design and surface roughness optimization were discussed. The combination of a 50 mL/rev integrated oil pump and 50 mL/rev independent oil pump driven by a 1500 rpm motor was the best oil supply design. Besides, decreasing the surface roughness parameter R_a of the disc specimens representing the cylinder holes to $0.4 \mu\text{m}$ can significantly decrease the wear rate. This work demonstrates the failed mechanism of crosshead-cylinder hole tribo-pairs in a reciprocating plunger pump and lubrication strategy, which has potential applications for improving the service life of plunger pump, and provides a valuable case study for understanding friction-induced failure in similar confined-sliding tribo-pairs beyond plunger pumps, such as in hydraulic actuators or valve guides.

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FAILURE ANALYSIS AND COUNTERMEASURES OF CROSSHEAD-CYLINDER HOLE TRI-BO-PAIR IN A RECIPROCATING PLUNGER PUMP

Summary

In this paper, the failure of the crosshead-cylinder hole tribo-pairs in a reciprocating pump is reported. The crank-connecting rod-crosshead mechanism was analyzed to obtain the velocity of the crosshead. The material, hardness, and roughness of the new crosshead and cylinder holes were determined. Macroscopic observations, material properties and roughness analyses, scanning electron microscopy (SEM) analyses, energy dispersive spectrometry (EDS) analyses, and lubricating oil quality analysis were conducted to clarify the potential reasons for the failure of the crosshead-cylinder hole tribo-pairs. Lubrication oil degradation is likely to cause the failure of the crosshead-cylinder hole tribo-pairs. The effects of the oil supply system design and surface roughness on the anti-wear behaviors of the crosshead-cylinder hole tribo-pairs are discussed.

Keywords: failure analysis, crosshead, cylinder hole, oil quality analysis, wear test.

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