Frictional behavior investigation on three types of PTFE composites under oil-free sliding conditions

Xue-Bin Yang
School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, People's Republic of China and
School of Civil Engineering & Architecture, Jiaxing University, Jiaxing, People's Republic of China

Xin-Qiao Jin and Zhi-Min Du
School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, People's Republic of China, and

Tian-Sheng Cui and Shao-Kan Yang
School of Energy and Power Engineering, Xi'an Jiao Tong University, Xi'an, People's Republic of China

Abstract

Purpose – The purpose of this paper is to investigate the frictional behavior of polytetrafluoroethylene (PTFE) composites under oil-free sliding conditions.

Design/methodology/approach – The friction force and power consumption of pressure packing seals, which were, respectively, made of common filled PTFE, 30 wt% CF (carbon fiber) + PTFE and C/C (carbon/carbon) + PTFE, are studied in a reciprocating oil-free compressor arrangement. Their coefficient of friction is tested on a block-on-ring type tribometer.

Findings – The results indicate that influence of mean sliding velocity on filled PTFE composites is apparently more predominant than the others. The friction force curvilinear path of 30 wt% CF + PTFE is hardly influenced by changing crankshaft turn angle. For C/C + PTFE, the effect of mean piston velocity on friction force is not evident. The results also indicate that the friction coefficient of C/C + PTFE is lower than that of 30 wt% CF + PTFE if their applied normal force exceeds 9.8 N. Furthermore, their variation curve of friction force is little different and the power consumption of C/C + PTFE is slightly higher than that of 30 wt% CF + PTFE.

Research limitations/implications – Neither the effect of real contact area on friction coefficient measured in a tribometer nor the influence of the temperature on friction force and power tested in a compressor is not taken into consideration here.

Practical implications – Owing to its good mechanical performances and frictional behaviors, C/C + PTFE is an optimum and promising material under conditions with sealing pressure up to 10 MPa and sliding velocity exceeding 4.0 m/s.

Originality/value – A novel material called C/C + PTFE is considered to make packing rings for oil-free reciprocating compressors and its friction behaviour is tested on a refitted compressor.

Keywords Friction measurement, Composite materials, Compressors

Paper type Research paper

1. Introduction

Some measures were taken for the purpose of pollution free and non-lubricated in dry running reciprocating compressors. Clearance seals were successfully used in labyrinth-piston compressors for helium (Kläy, 1975), CO_2 (Baumann and Conzett, 2002) or other technical gases (Baumann, 1994), sealing with a minimal well defined gap of 4-6 μm in diameter between piston and cylinder. The other case is utilized water as lubrication (Coney *et al.*, 2002) which quasi-isothermal compression is achieved by the injection of a large quantity of water through spray nozzles inside the cylinder. Although these oil-free compressors have been developed for different running conditions, mechanical seals with contact counterparts are necessary in many cases.

Polytetrafluoroethylene (PTFE) significantly exhibits self-lubricating characteristics and is currently utilized in high performance mechanical seals. Its transferred layer formation starts from the strong fixing polymer particle onto the frictional counterparts surface in the contact zone (Pleskachevsky and Smurugov, 1997). Unfortunately, the friction force of PTFE provides abrupt increase and shows a high wear rate as a function of elevated normal load (Stuart, 1998). One or two or even more kinds of reinforcement filler materials were complemented to improve the tribological behaviors of PTFE-based composites. This situation is virtually identical in the fields of dynamic seals for reciprocating gas compressors. One example as illustrated is that the epoxy-bonded composites were described and compared with the common filled PTFE for rod packing assemblies in non-lubricated reciprocating compressor (Maer *et al.*, 1973). But some of them, whose lifetime could not exceed 4,000 h in view of their poor wear resistance, are still not suitable to operate at sealing pressure up to or beyond

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0036-8792.htm

Industrial Lubrication and Tribology
61/5 (2009) 254–260
© Emerald Group Publishing Limited [ISSN 0036-8792]
[DOI 10.1108/00368790910976087]

about 10 MPa and mean piston speed of more than 4.0 m/s. Some filler materials are effective in obstructing the large-scale fragmentation from the polymer composites resulting in formation of small discontinuous fragments, but they tend to undergo fracture under heavy loading conditions and cause abrasion to the contact surface (Unal *et al.*, 2006).

Carbon fiber (CF) reinforced carbon matrix composites (C/C – carbon/carbon composites), have been widely used in many military and civil fields due to their high mechanical properties at elevated temperature, good thermal conductivity, low coefficient of thermal expansion, longer service life, excellent ablation resistance, and superiority at high temperature. While some heat treatment processes are conducted to improve friction and wear properties of C/C composites, the coefficients of friction are even beyond 0.3 (Luo *et al.*, 2003). A friction coefficient decrease near to 0.10 was obtained from tests at the temperature of above 373 K, unfortunately, the wear rates presented a steep slope with increasing temperature (Gomes *et al.*, 2001). Also, the discussion above had argued that the substantive application of C/C composites could not be operating reliably in the pressure packing or piston rings for reciprocating compressors with oil-free lubrication.

The increase of hardness values and thermal conductivity can improve the tribological properties of PTFE composites. Thus, a novel material far from oil lubrication, which comprehensively takes the excellent mechanical performance of C/C composites and the self-lubricating properties of PTFE into account, are presented in this paper. That is the so-called C/C + PTFE composites, which are made by the infiltration process with three-dimensional multi-directional braided C/C composites exposed in PTFE vapor. Then, nanometer PTFE could be homogeneously incorporated and dispersed into the C/C composites under high pressure and temperature conditions.

Although there are a number of studies on PTFE (Pleskachevsky and Smurugov, 1997; Unal and Mimaroglu, 2003) or its filled composites (Han *et al.*, 2001; Myshkin *et al.*, 2005; Tevrüz, 1998; Tevrüz, 1999), some aspects of tribological properties still require further investigation for C/C + PTFE composites especially as packing rings operating under reciprocating sliding conditions. The results, investigated on the effect of normal load and sliding velocity on the friction coefficient of three types of PTFE self-lubricated composites tested in a block-on-ring tribometer, are presented in this paper. Further, friction force and power consumption tested on a refitted reciprocating gas compressor under oil-free lubrication are also studied. The results of C/C + PTFE are compared with that of the other materials. One is the common filled PTFE used in non-lubricated conditions. This composite usually consists of PTFE reinforced with conventional filler additions such as bronze powder, glass fiber, graphite and silicon dioxide, etc. The other is 30 wt% CF + PTFE which is made of PTFE incorporating 30 wt% CFs.

2. Test apparatus for coefficient of friction

Friction coefficient was tested on a block-on-ring type tribometer (shown in Figure 1) at room temperature under dry self-lubricating conditions. The dimensional details of the rotating ring and the three type materials of specimens are presented in Figure 2. The arithmetical mean deviation of the profile was employed to express the surface roughness of the specimens. The initial surface roughness exhibits approximate values of 0.24 μm for filled PTFE, 0.31 μm for CF + PTFE and 1.86 μm for C/C + PTFE. The rotating ring was made of 45# steel and its surface was treated the same as the piston rod used in tribological behavior test apparatus. The specific test conditions of the experimental specimens are given in Table I. Considered the poor mechanical properties, the sample of filled PTFE was tested under lower load than the other two samples in order to reduce the effect of real contact area on friction coefficient due to wider grinding track.

Figure 1 A view of friction coefficient test rig

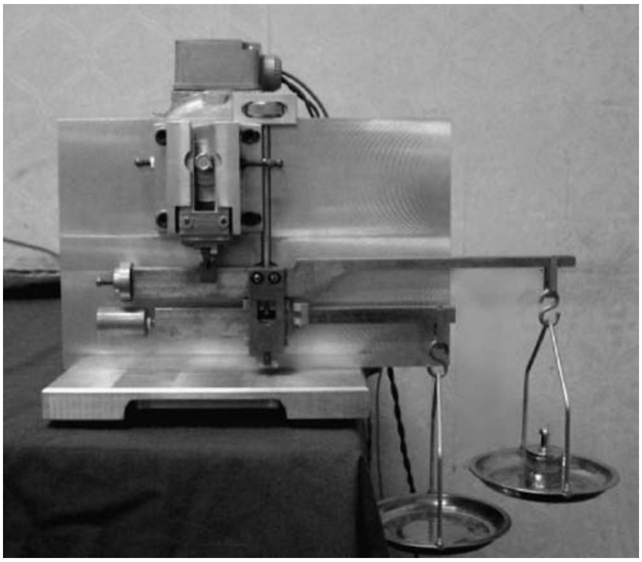
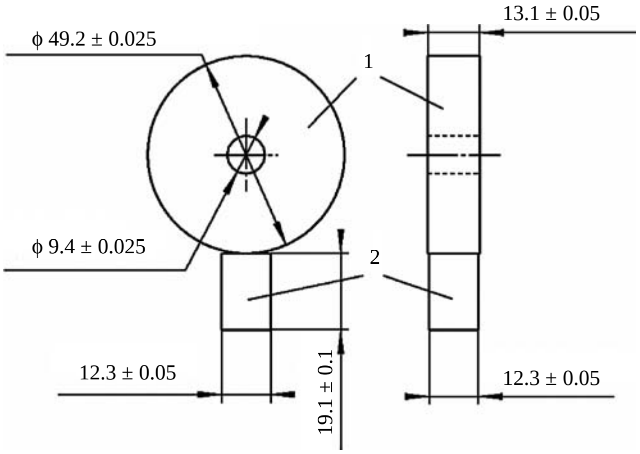


Figure 2 Schematic diagram of the frictional pair



Notes: 1. Rotating ring; 2. specimen

3. Friction force experimental details

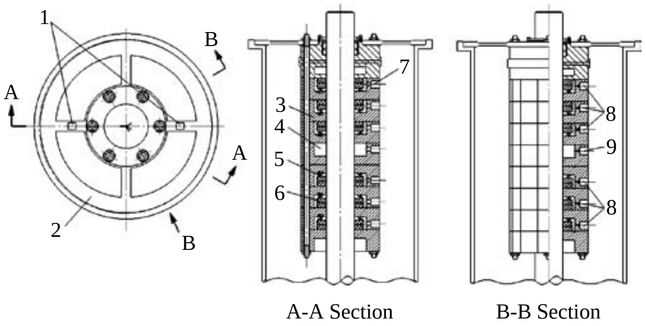
3.1 Apparatus

Frictional testes were carried on a refitted vertical gas compressor shown schematically in Figure 3. Cylinder and piston were removed, and seven static stuffing boxes were assembled on a reciprocating piston rod. Frictional behaviors of pressure seals for three different materials were tested at

Table I Specific test conditions of the experimental samples

Rotate speed of ring (rpm)	Circular velocity (m/s)	Load (N) Filled PTFE	30 wt% CF + PTFE	C/C + PTFE
500	1.28	2.45	9.8	9.8
1000	2.57	4.9	19.6	19.6
1500	3.85	7.35	29.4	29.4
2000	5.13	9.8	39.2	39.2

Figure 3 Pressure packing arrangement



Notes: 1. Resistance strain sensor for friction force measurement; 2. spoke 3. static stuffing box; 4. pressure chamber; 5. axial retainer spring; 6. seal ring; 7. bore for thermocouple probe; 8. bore for manometer connection; 9. bore for constant-pressure air

room temperature of 293 K. Two segmented packing rings in PTFE composites were fixed in each box except the middle stuffing box (4 in Figure 3) by three axial retainer springs. The high-pressure gas supplied by another gas compressor flowed into no. 4 box, and formed a constant pressure chamber that is like a pressure cylinder. Piston rod was made of 45# stainless steel materials whose surface showed a roughness value of 0.4-0.1 μm and rigidity of HRC 60.

3.2 Test seals

Three different materials of seal rings, which employed three-piece tangential cut type (Graunke, 1996), were tested on the apparatus. Their mechanical and thermal properties are presented in Table II. The results of friction force and power were measured in the duration stage after each material of sealing rings and piston rod had run for 80 h. In many oil-free lubricated reciprocating motions, this is practically a useful stage.

Table II Mechanical and thermal properties of seal rings

Properties	Filled PTFE	30 wt% CF + PTFE	C/C + PTFE
Density (g/cm^3)	2.25 ± 0.03	2.1 ± 0.02	1.6-1.8
Compressive strength (MPa)	8-9.8	3.81	50
Tensile Strength (MPa)	7-11.8	15.7	58-60
Elongation percentage (%)	190-200	381	–
Wear mass (g/h)	–	0.0014	0.0002
Thermal conductivity [W/(k m)]	12.5	–	97

3.3 Transient piston speeds

The maximum piston speed occurs not on but before or after the center position of a stroke. Its value is concerned not only with crank radius, angular velocity and crank angle, but also with connecting rod length/crank radius ratio. Connections between transient piston speed and crank angle under various crank rotational speeds in one period are shown in Figure 4. Table III presents the operating piston speeds for various crankshaft rotational speeds.

4. Results and discussion

4.1 Friction coefficient

Figure 5 illustrates the variation trends of friction coefficient with sliding velocity of 0.4, 1.2 and 2.0 m/s and normal load of 1.0 and 2.0 MPa. It is observed that when the load increases, for three materials of samples, the coefficient gradually decreases except that the velocity is less than 2.6 m/s for C/C + PTFE. It is similar to some reports (Myshkin *et al.*, 2005; Tevrüz, 1998; Tevrüz, 1999) about PTFE composites.

The main reason of this is that PTFE self-lubricating film transfers more conveniently to piston rod surface resulting

Figure 4 Transient piston speed vs crank angle in one period (Crank angle is 0 rad when the volume of cylinder is minimum)

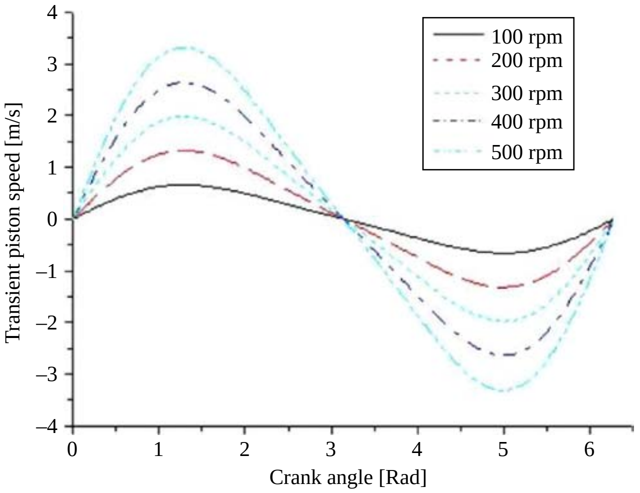
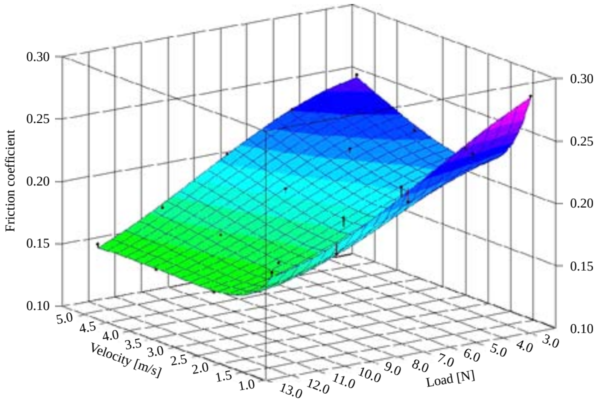


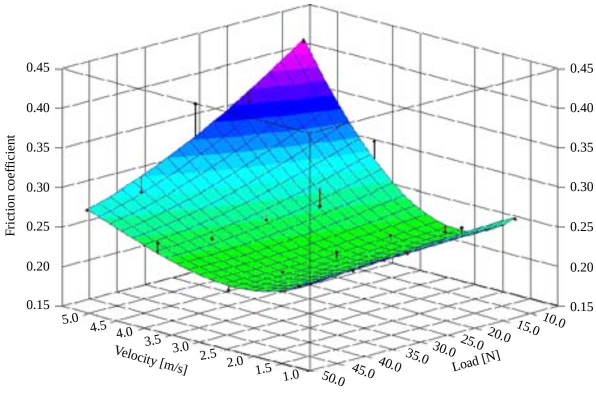
Table III Operating piston speeds for various Crankshaft rotational speeds

Crankshaft rotational speed (rpm)	Crank angular velocity (rad/s)	Mean piston speed (m/s)	Maximum piston speed (m/s)
100	10.47	0.4	0.66
200	20.94	0.8	1.32
300	31.42	1.2	1.98
400	41.89	1.6	2.64
500	52.6	2	3.31

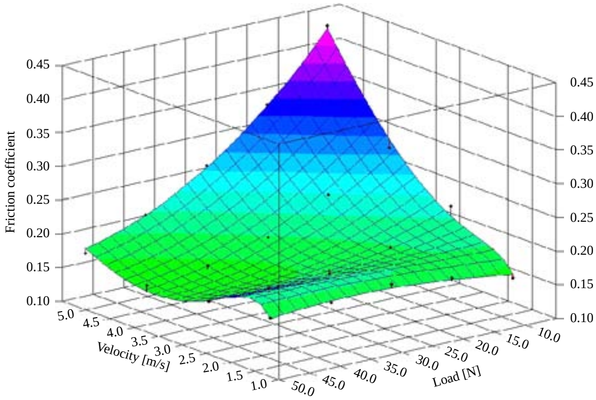
Figure 5 Friction coefficient vs mean piston speed and radial pressure for oil-free packing rings



(a) Filled PTFE rings



(b) 30wt% CF+PTFE rings



(c) C/C+PTFE rings

from the heavier load capacity. C/C + PTFE possessed lower coefficient than 30 wt% CF + PTFE when the normal load value is more than 9.8 N. This suggests that C/C + PTFE offers attractive features such as stronger mechanical strength, higher surface hardness, and better conductivity that it can significantly reduce the actual contact frictional area and form a thin and tenacious transfer film on the counterpart surface, although these properties also lead to adverse results under the load of less than 9.8 N and the velocity over 3.8 m/s.

The results shown in Figure 5 also indicate that the friction coefficient of filled PTFE is more sensitive to the change of speed. In addition, the friction coefficient of C/C + PTFE sliding on piston rod made of 45# steel is below 0.15 when its normal load is greater than 9.8 N and sliding velocity is beyond 3.5 m/s. With the increase of the sliding velocity, the coefficient of filled PTFE increases first, then decreases and increases again after passing through a minimum value. These trends are the same as the coefficient of C/C + PTFE when its load is more than 19.6 N. With the increase of the sliding velocity, the coefficient of filled PTFE decreases from a higher value, then increases after passing through a minimum value. The position of the minimum occurs when the sliding velocity is in the range of 2.5-3.5 m/s. The trends are similar with that of 30 wt% CF + PTFE. When the load is more than 19.6 N, the coefficient of C/C + PTFE increases first, then decreases from a higher value, and then increases again after passing through a minimum value. C/C + PTFE and 30 wt% CF + PTFE 30 wt% CF + PTFE and C/C + PTFE have the more similar change trends that the coefficient increases dramatically as the velocity is more than 2.6 m/s, although the coefficient of 30 wt% CF + PTFE only decreases firstly and then increases with velocity increase. It can be determined that the mechanical properties of materials play an important role in the speed impact on friction coefficient, especially when the load exceeds a certain value. The average yield stress value of PTFE friction surface is so high that PTFE wear debris accumulation is difficult to be embedded into the PTFE matrix.

Sliding velocity will give rise to heat generation, deformations, chemical changes and wear, and so on, thus friction coefficient changes. In the lower velocity, this accumulation played a part of solid lubricant, so along with the increased speed, lubrication increases and friction coefficient decreases. While speed exceeds a certain value, the coefficient increases as a result of the undermined friction surface integrity of solid lubricant. The higher mechanical strength and hardness the materials have, the less effect on coefficient the speed change provides, especially when the load value is higher.

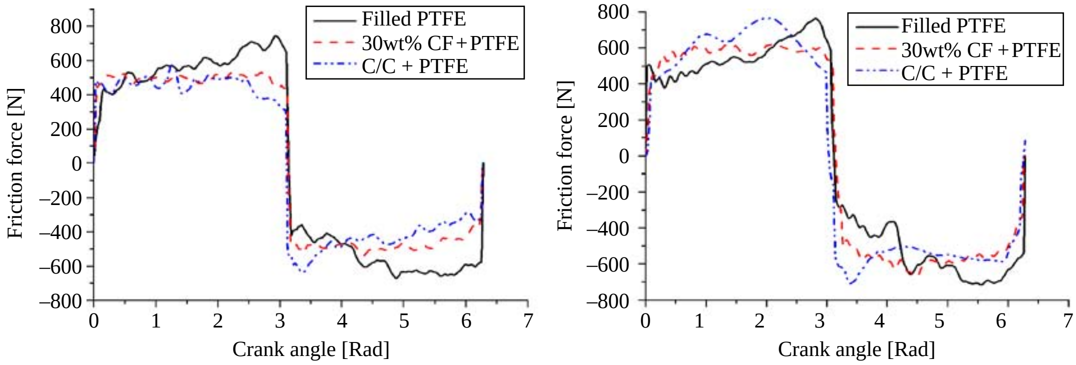
Whenever the filled PTFE rings exhibit the least coefficient as seen in Figure 5, it possesses the maximal specific wear rate under higher pressure and velocity conditions due to its poor mechanical strength and surface hardness. Meanwhile, 30 wt% CF + PTFE possessed higher coefficient than C/C + PTFE at the normal load value of beyond 9.8 N. Therefore, C/C + PTFE seal rings is the most suitable to be used in higher pressure and velocity amongst the three types of rings.

4.2 Friction force

Figure 6 shows that friction force for twelve packing rings increases with the increase of sealing pressure. It can also be concluded that the force varies with the transient piston speed value. If the sealing pressure is higher, the transient piston speed exhibits less effect on friction force value. Consequently, the force curve wave is closer to the rectangular wave. Spring pre-tightening force is the single normal load applied on the piston rod under no sealing pressure conditions. The results presented in Figure 6 also indicate that the friction force is far from direct proportional to the normal load.

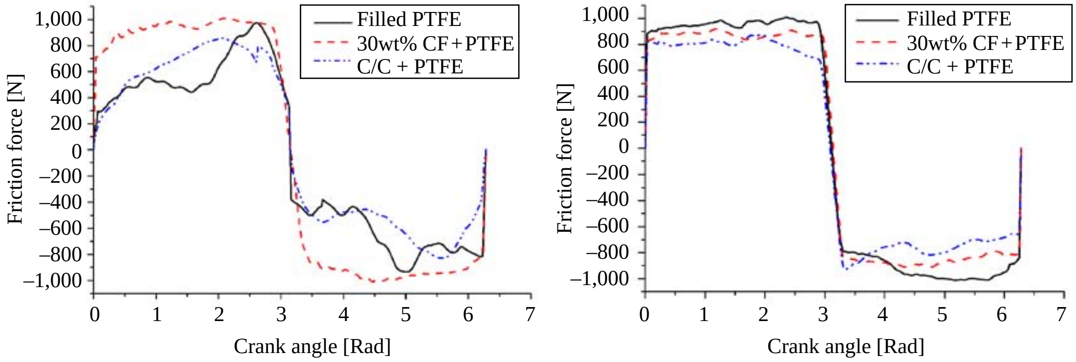
A likely explanation for the experimental results is that, to some extents, friction force may be as a function of load, sliding velocity, temperature, interfacial bond strength, real contact area and other factors. From the polymers perspective

Figure 6 Variation of friction force in a piston cycle for three materials



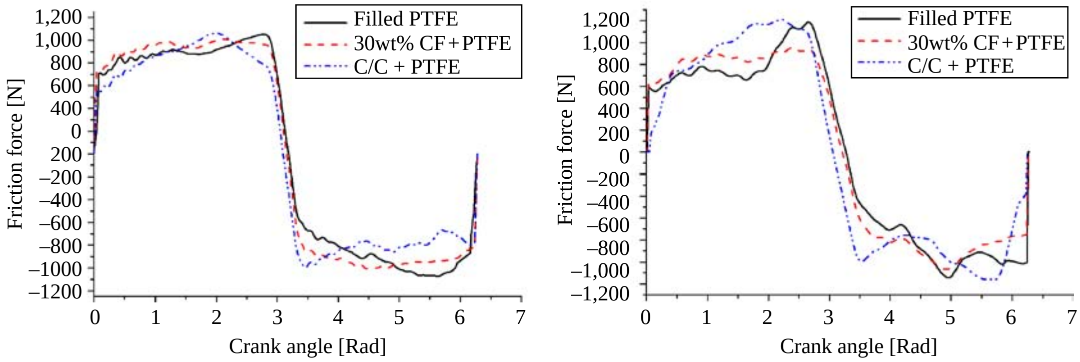
(a) 1 MPa, 0.4 m/s

(b) 1 MPa, 1.2 m/s



(c) 1 MPa, 2.0 m/s

(d) 2 MPa, 0.4 m/s



(e) 2 MPa, 1.2 m/s

(f) 2M Pa, 2.0 m/s

of tribological behavior (Myshkin *et al.*, 2005), the source of the frictional force is attributed to the junctions sheared and breakdown of the interfacial adhesion bonds under the applied tangential force, deformation occurring when the asperities of two sliding surfaces come into contact with each other, and the real contact area that the opposing asperities with maximum height come into contact and the new pairs of asperities with lesser height make contact forming individual spots if the load increases.

When the applied normal load and mean piston velocity is lower, 30 wt% CF + PTFE and C/C + PTFE exhibited the more gentle variation than filled PTFE. Mainly because filled PTFE materials exhibit the least mechanical strength and surface hardness, the curve of friction force for filled PTFE rings changes apparently with the crank angle cyclic variation. It is demonstrated that the friction force of this rings is the most sensitive to the transient piston speed under lower pressure. However, C/C + PTFE revealed higher surface hardness and better thermal conductivity, since a slight gradual variation of friction force is observed in Figure 6. Only when the sealing pressure is more than 1.0 MPa, the friction force variation of filled PTFE decreases with the increase of crank angle, but increase again with the mean sliding speed of 2.0 m/s. Strong adhesive bonding occurs for mental in sliding contact with PTFE polymers and different surface properties of contact region influence tribological performance (Buckley, 1982).

C/C + PTFE displays more drastic variation with the cyclic transient velocity than 30 wt% CF + PTFE mainly attributed to its excellent mechanical properties. It is believed that the formation of PTFE self-lubricating films provides substantial changes to the frictional behavior of C/C composites in the sliding contact against a stainless steel counterface. However, the presence of carbon particles could plough the matrix and destroy the transfer film formed on the counterpart surface (Khedkar *et al.*, 2002). Consequently, the wear debris generated, which could not be inserted into the gap of matrix in time, thin the PTFE transfer film especially at higher transient velocity. In addition, carbon debris particle presented impedes the build up process of PTFE film. For 30 wt% CF + PTFE with less surface hardness, the probability for embedding into the soften matrix is slight more than C/C + PTFE to reduce the damage of transfer film. But excellent mechanical properties is more effective in decreasing wear rate, hence generally speaking, C/C + PTFE is more reliable than 30 wt% CF + PTFE under conditions with heavier sealing pressure, higher transient sliding velocity and even longer sliding distances.

When compared with the results of Section 4.1, it can be concluded that the lowest coefficient does not consequentially lead to the lowest friction force while the load is a constant value. This indicates that the friction coefficient is not only a function of normal load, transient sliding velocity, actual contact area and even frictional temperature, but also concerned with the mechanical properties, surface hardness and other natures.

4.3 Power consumption

As shown in Table IV, the power of filled PTFE presents a maximum consumption value at the same pressure and speed. The next is C/C + PTFE and the minimum is 30 wt% CF + PTFE. Power consumption is irregularly affected by mean piston speed, while it is approximately proportional to the value of sealing pressure. When the sealing pressure is a constant value, the influence of average piston speed on power consumption of C/C + PTFE is less than the two other materials.

Filled PTFE rings had the lowest friction coefficient and the minimum could be up to 0.14 as seen in Figure 5, but it had the highest power consumption due to its poor thermal conductivity, heat resistance and high temperature creep resistance.

5. Conclusion

The following conclusions can be drawn from this work.

First of all, if normal load is more than 9.8 N, the friction coefficient of the three types of rings showed the following order: 30 wt% CF + PTFE > C/C + PTFE > filled PTFE. If radial pressure is less than the preceding detailed value, the order was: C/C + PTFE > 30 wt% CF + PTFE > filled PTFE.

Table IV Comparison of power consumption for three materials of rings

Speed (m/s)	Sealing pressure (MPa)	Power consumption (kW) Filled PTFE	 30 wt% CF + PTFE	 C/C + PTFE
0.4	0	2.88	2.7	3.12
	1.0	4.5	3.3	4.02
	2.0	5.82	4.32	4.98
1.2	0	4.02	3.6	4.02
	1.0	5.52	4.2	5.1
	2.0	7.08	4.98	5.94
2.0	0	4.86	4.32	4.92
	1.0	6	5.16	5.94
	2.0	8.16	5.64	6.96

Second, filled PTFE rings exhibit the lowest friction coefficient and the minimum could be up to 0.14, but its friction force is sensitive to the transient sliding speed and it had the highest power consumption.

Third, lower coefficient of friction answered by classic tribological theory does not mean slower friction force and power consumption. At various sliding velocity, to put it another way, friction force is not always proportional to coefficient when the applied normal load is a constant value.

Moreover, C/C + PTFE seal rings is the most suitable to be used under conditions with sealing pressure up to 10 MPa and sliding velocity of over 4.0 m/s amongst the three types of rings, due to its better tribological properties with better wear resistance, lower friction force and power consumption. And its serve life will be expected to exceed 8,000 h.

Finally, further investigations about C/C + PTFE should be carried on to improve brittleness, to intensify oxidation resistance at elevated temperature and to enhance triobological properties with three-dimensionally braided characteristics of C/C composites. Furthermore, expanded mass production and improved manufacturing processes should be seriously treated to reduce its relatively expensive cost for larger scale applications in the field of piston rings and pressure packing with oil-free lubrication.

References

Baumann, H. (1994), "Design features of a small oil-free, reciprocating, high pressure compressor", *Proceedings of 1994 International Compressor Engineering Conference at Purdue, West Lafayette, Indiana*, pp. 381-5.

Baumann, H. and Conzett, M. (2002), "Small oil free piston type compressor for CO_2", *Proceedings of 2002 International Compressor Engineering Conference, Purdue, West Lafayette, Indiana*, pp. C23-5.

Buckley, D.H. (1982), "Surface films and metallurgy related to lubrication and wear", *Progress in Surface Science*, Vol. 12 No. 1, pp. 1-153.

Coney, M.W., Stephenson, P., Malmgren, A. and Linnemann, C. (2002), "Development of a reciprocating compressor using water injection to achieve quasi-isothermal compression", *Proceedings of 2002 International Compressor Engineering Conference, Purdue, West Lafayette, Indiana*, pp. C3-4.

Gomes, J.R., Silva, O.M., Silva, C.M., Pardini, L.C. and Silva, R.F. (2001), "The effect of sliding speed and temperature on the tribological behaviour of carbon-carbon composites", *Wear*, Vol. 249, pp. 240-5.

Graunke, I.K. (1996), "Development in dry running seals for reciprocating compressors", *Proceedings of 1996 International Compressor Engineering Conference, Purdue, West Lafayette, Indiana*, pp. 251-6.

Han, Y.Ch., Schmitt, S. and Friedrich, K. (2001), "Microfriction studies of filled PPS/PTFE-composite blends", *Industrial Lubrication & Tribology*, Vol. 53 No. 1, pp. 32-42.

Khedkar, J., Negulescu, I. and Meletis, E.I. (2002), "Sliding wear behavior of PTFE composites", *Wear*, Vol. 252, pp. 361-9.

Kläy, H.R. (1975), "Reciprocating compressors with labyrinth pistons for helium", *Cryogenics*, Vol. 15 No. 10, pp. 569-71.

Luo, R.Y., Huai, X.L., Qu, J.W., Ding, H.Y. and Xu, S.H. (2003), "Effect of heat treatment on the tribological behavior of 2D carbon/carbon composites", *Carbon*, Vol. 41, pp. 2693-701.

Maer, P.S., Mitchell, P.J. and Atkins, B.R. (1973), "Multi-phase filled-plastics piston rings for non-lubricated compressors: a comparison of the performance of filled PTFE and epoxy-bonded materials in dry gases", *Tribology*, Vol. 6 No. 4, pp. 129-34.

Myshkin, N.K., Petrokovets, M.I. and Kovalev, A.V. (2005), "Tribology of polymers: adhesion, friction, wear, and mass-transfer", *Tribology International*, Vol. 38 Nos 11/12, pp. 910-21.

Pleskachevsky, Y.M. and Smurugov, V.A. (1997), "Thermal fluctuations at PTFE friction and transfer", *Wear*, Vol. 209, pp. 123-7.

Stuart, B.H. (1998), "Tribological studies of poly(ether ether ketone) blends", *Tribology International*, Vol. 31 No. 11, pp. 647-51.

Tevrüz, T. (1998), "Tribological behaviours of carbon filled polytetrafluoroethylene (PTFE) dry journal bearings", *Wear*, Vol. 221 No. 1, pp. 61-8.

Tevrüz, T. (1999), "Tribological behaviours of bronze-filled polytetrafluoroethylene dry journal bearings", *Wear*, Vol. 230 No. 1, pp. 61-9.

Unal, H. and Mimaroglu, A. (2003), "Influence of test conditions on the tribological properties of polymers", *Industrial Lubrication & Tribology*, Vol. 55 No. 4, pp. 178-83.

Unal, H., Mimaroglu, A. and Arda, T. (2006), "Friction and wear performance of some thermoplastic polymers and polymer composites against unsaturated polyester", *Applied Surface Science*, Vol. 252, pp. 8139-46.

Corresponding author

Xin-Qiao Jin can be contacted at: xqjin@sjtu.edu.cn