Experimental study on tribological characteristics in coke powder lubrication

Jin Xiang and Zheng Yan

Abstract
Pushing coke is an important process in coke oven production. In the process of pushing coke, under the three-body contact state of steel, coke powder, and refractory brick, coke powder plays an important role in lubrication. In this article, a study on the macro- and micro-behavior and mechanism of coke powder lubrication is carried out through tribological tests. The results show that in the process of sliding friction, coke powder plays a role of lubrication through forming a powder layer and shearing occurred inside the powder layer. The load keeps at 5 MPa, under the lower velocity, the powder layer is thinner and delamination occurred in local position. While under the higher velocity, the coke powder can form a compact and complete powder layer and exhibit better lubrication characteristics. However, when the velocity increases to 0.52 m/s, the continuous powder layer is not formed, so the friction coefficient is higher, the frictional surface wears seriously and results in vibration to occur. The velocity keeps at 0.40 m/s, and the powder layer inclines to deteriorate under higher load. When the load increases to 20 MPa, a part of the powder layer is damaged, and severe wear occurs on the surface.

Keywords
Coke powder, powder layer, lubrication characteristics, friction coefficient

Date received: 28 February 2020; accepted: 10 June 2020

Handling Editor: Michal Kuciej

Introduction
Coke oven production is beneficial for the comprehensive utilization of coal, plays an important role within the metallurgical industry, and as such, occupies a pivotal position in the Chinese economy. The coke pushing rod is the core equipment of the coke oven production, it’s a box structure with the length of 27 m, width of 0.40 m, height of 5.65 m and weight of 40 tons, which mainly consists of a coke pushing head, rod, and slipper, and a three-dimensional model of the coke pushing rod is shown in Figure 1.

Figure 2 presents the three-dimensional model of coke pushing process. It can be seen that the coke pushing rod is driven by a gear, and the coke is pushed out from the carbonization chamber via a coke pushing head. During the coke pushing process, due to there is a gap between the coke pushing head and ground of the carbonization room (it is made of refractory bricks), resulting in a very small amount of coke not being pushed out from the carbonization chamber to form powder under pressure. After the slipper enter the carbonization room, friction is generated by the bottom of the slipper contacting with the ground of the carbonization chamber, while the coke powder plays a very important role in lubrication.
As an effective and promising lubrication method, solid lubricants are widely used in many industrial fields, such as bearing, casting, and milling\textsuperscript{1–3}. In addition, solid lubricants can strongly bond with a surface using proper adhesives, reducing the friction coefficient, and prolonging the service life.\textsuperscript{4} The matrix form composites by adding solid lubricants, and the composites have good lubrication performance.\textsuperscript{5}

Many factors, such as the amount of properties of the solid lubricant can affect the characteristics of composite materials.\textsuperscript{6,7} Li et al.\textsuperscript{8} studied the tribological performance of B\textsubscript{4}C-hBN composite ceramics with different contents of hBN (0, 5, 10, 20, and 30 wt%) against AISI 321 steel under distilled water condition, and the results show that as the hBN content increases, the steady-state coefficient of friction of the pairs of B\textsubscript{4}C-hBN/AISI 321 steel decreases significantly, and the coefficients of wear of both B\textsubscript{4}C-hBN pin and AISI 321 steel disk samples have a reducing trend. Shi et al.\textsuperscript{9} prepared NiAl matrix self-lubricating composites with different solid lubricant additions (PbO, Ti\textsubscript{3}SiC\textsubscript{2}-MoS\textsubscript{2}, Ti\textsubscript{3}SiC\textsubscript{2}-WS\textsubscript{2}) by SPS. Due to MoS\textsubscript{2} lubricated better at low temperatures, while Ti\textsubscript{3}SiC\textsubscript{2} lubricated better at high temperatures. The Ti\textsubscript{3}SiC\textsubscript{2}-MoS\textsubscript{2} binary lubricant presented the best synergetic lubricating effect.

Velocity and load affect the lubrication performance of solid lubricants.\textsuperscript{10,11} Wang et al.\textsuperscript{12,13} carried out the ring-on-flat experiments to analyze the effects of the sliding velocity and load on graphite powder lubrication characteristics. Graphite powder has good lubrication characteristics under higher velocity and lower load. Abdullah et al.\textsuperscript{14} prepared a novel graphene-zinc oxide composite film, as a solid-state lubricant. The tribological performance was measured under ambient conditions using a ball-on-disk tribometer with contact pressures up to 1.02 GPa, the lubricant demonstrated substantial friction and wear reduction (ca. 90%) compared to non-lubrication.

However, in the pushing coke process, in the case of refractory bricks for grinding parts, the study on the friction characteristics of coke powder lubrication has not been found. In this article, under the contact state of steel, coke powder, and refractory brick, the friction characteristics of coke powder lubrication were studied through tribological tests. First, the microcrystalline structure of coke powder was studied by X-ray diffraction (XRD). Second, the effects of non-lubrication and coke powder lubrication on the friction interface were compared. In addition, the effects of the sliding velocity and load on the coke powder lubrication were studied. Meanwhile, the formation and damage mechanism of the powder layer were discussed, and the lubrication characteristics of the coke powder in a frictional interface were revealed.

**Experiment**

**Tribological experiment**

Tribological tests were performed experimentally using a ball-on-disk high-temperature tribometer. The upper
sample was a ball with a diameter of 6 mm and the material is ordinary carbon structural steel with grade Band surface roughness Ra of 0.68 μm. The lower sample with a dimension of 19 mm × 19 mm × 7 mm was made of refractory brick with hardness 6.5 HM and a surface roughness Ra of 13.26 μm. The coke powder used in the tests was 50 μm, and the amount of coke powder is 2 g in each experiment, and the test schematic is shown in Figure 3.

The sliding velocity of the lower sample reached to 0.15, 0.30, 0.40, and 0.52 m/s, respectively. Meanwhile, the load was applied along the vertical axis of the upper sample, and the value reached to 5, 10, 15, and 20 MPa, respectively, the test temperature was 20°C and the test time is 150 s.

Characterization

XRD analyses were performed using Cu-Kα radiation, generated at 40 kV and 100 mA. Scans were performed at a rate of 1.0°min⁻¹ for 20 values between 10° and 90°.

The surface topography of the samples was characterized by scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectrometry (EDS).

Results and discussion

Tribology characteristics of coke powder lubrication

Microcrystalline structure of coke powder. Coking coal contains a large amount of organic matter and a small amount of inorganic mineral. Organic matter is a high molecular polymer formed by the aromatic nucleus. The basic structural unit is a polymerized aromatic nucleus with side chains around it. During the high-temperature pyrolysis process, the aromatic nuclear condensation and thickening cyclization, and the side chains falling off and decomposing in succession, form the microcrystalline structure of the coke.¹⁵,¹⁶

The XRD pattern of coke powder is shown in Figure 4. There are two sharp intensity bands in the XRD pattern of coke powder, corresponding to the crystal surface index (002) and (100) respectively. (002) diffraction peak indicates the degree of parallel and azimuth orientation of aromatic layers, the higher the intensity, the smaller the width, and the better the degree of orientation of the layer. (100) diffraction peak represents the aromatic size, the higher the intensity, the smaller the width, the larger the size of the layer, and the higher the degree of condensation of the aromatic nucleus.

(002) and (100) diffraction peaks at 2θ = 26.34° and 43.15°. The crystalline parameters (d₀₀₂, Lc) and graphitization degree parameter (g) are calculated using the Bragg equation,¹⁷ Scherrer equation, and Mering–Maire equation, respectively.¹⁸ The microcrystalline structure parameters of the coke powder are shown in Table 1

\[
d₀₀₂ = \frac{\lambda}{2 \sin \theta_{002}} \tag{1}
\]

\[
L_c = \frac{0.89 \lambda}{\beta \cos \theta_{002}} \tag{2}
\]

\[
g = \frac{0.3440 - d_{002}}{0.3440 - 0.3354} \tag{3}
\]

where \(d_{002}\) is the interlayer spacing, \(\lambda\) is the X-ray wavelength (0.14506 nm), \(L_c\) is the average crystalline
thickness, $\beta$ is the full width at half the maximum intensity of the (002) diffraction peak, and $2\theta$ is the peak position.

The crystalline parameters of the coke powder indicate that during the process of coking coal pyrolysis to form the microcrystalline structure of coke, the interlayer spacing $d_{002}$ decreases and the microcrystalline size $L_c$ increases continuously. The aromatic layer structure of carbon atoms of coke powder tends to the aromatic lamellar structure of graphite carbon atoms, and the carbon atoms transform from the random layer structure to the ordered structure of graphite crystal,\textsuperscript{19} that is, the microcrystalline structure of the coke powder is graphitization, and the graphitization degree is 64.05%.

**Tribology characteristics of non-lubrication and coke powder lubrication.** Test conditions: the load is 5 MPa, and the velocity is 0.40 m/s, non-lubrication, and coke powder lubrication, and the duration time is 60 s.

Figure 5 shows the friction coefficients of non-lubrication and coke powder lubrication. It can be observed that the friction coefficient of non-lubrication is 0.79, which is obviously higher than that of coke powder lubrication. Due to coke powder lubrication, the friction occurs inside the powder layer with low shearing,\textsuperscript{20} so the friction coefficient is lower, however, during the non-lubrication test, the upper and lower samples surface contact and rub against each other, so friction coefficient is higher, due to the higher friction coefficient, vibration occurs in the upper sample continuously. At 60 s, serious vibration occurs in the upper sample and the test stops.

Figure 6(a) shows the SEM micrograph of the frictional surface of non-lubrication. It can be seen that due to no lubrication, the upper and lower samples surface contact and rub against each other, resulting in a large number of deep and long grooves. Meanwhile, plastic deformation occurs in some position, some large particles of abrasive debris enter the matrix and form bulges, and a large number of debris adhere to the friction surface. So, serious wear occurs on the frictional surface. Figure 6(b) shows the SEM micrograph of the frictional surface of coke powder lubrication. Due to the refractory brick that is hard and brittle, during the sliding friction, some abrasive debris are generated. There are scratches that appear on the frictional surface due to the effect of the abrasive hard particles,\textsuperscript{21} while some abrasive particles adhere to the frictional surface. The above analysis indicates that coke powder plays a very important role in lubrication.
Effect of sliding velocity on friction coefficient and powder layer

Friction coefficient. During the test, when the velocity increases to 0.52 m/s, due to the higher velocity, a large number of the powder is thrown out of the friction interface, and vibration occurs in the upper sample continuously. At 150 s, serious vibration occurs in the upper sample and the test stops.

Figure 7 shows the friction coefficient under different sliding velocities. It can be seen that the load keeps at 5 MPa, the friction coefficient is lower with the increasing sliding velocities, while the friction coefficient increases suddenly when the sliding velocity increases to 0.52 m/s. The main reason for this phenomenon is that the powder layer is easier to form when the sliding velocity is higher, so that the friction occurs inside the powder layer with low shearing, so the friction coefficient is lower. Too high sliding velocity causes a large amount of coke powder to be thrown out of the friction interface, not prone to form the powder layer, so the friction coefficient is highest, and resulting in the vibration to occur.

Microstructure and elemental proportion of powder layer. Figure 8 shows the SEM micrographs of the powder layer surface under different velocities. Table 2 lists the weight percentages of the three main elements, C, Fe, and Si on the powder layer surface. As shown in Figure 8(a)–(c) and Table 2, a layer of powder is formed on the friction surface.

As shown in Figure 8(a) and Table 2, the weight proportion of the C element is 5.90% on the powder layer surface. Due to the lower velocity, the powder layer is very thin, the coke powder lubrication is limited, the interfacial shearing mainly occurs between the powder particles and the friction surfaces or inside the powder layer, so the friction coefficient is higher. Besides, effect of abrasive hard particles results in more scratches appeared on the powder layer surface, and some large abrasives enter the matrix, forming bulges.

As shown in Figure 8(b) and Table 2, the weight proportion of the C element is 7.52% on the powder layer surface, forming a thinner powder layer. The lubrication of coke powder is limited, although the interfacial shearing still occurs mainly between the powder particles and the friction surfaces or inside the powder layer, however, the friction coefficient begins to decrease with the increase of the velocity. The effect of abrasive hard particles results in the scratches that appeared on the powder layer surface. Meanwhile, delamination occurs in the powder layer. The mechanism for this phenomenon is that shearing occurs inside the powder layer and delaminates the powder layer into several sub-layers, which can be carried by the rotating lower sample or remain on the upper sample separately. It can be concluded that the powder layer is thinner and is prone to delamination due to adhesion with the upper sample surface weakening.

As shown in Figure 8(c) and Table 2, the weight proportion of the C element is 18.55% on the powder layer surface, forming a compact and complete powder layer. Interfacial shearing mainly occurs inside the powder layer, so the friction coefficient is low. The shearing of the powder layer makes the powder particles aggregation, forming slight spot aggregation.

From Figure 8(d), it can be observed that no continuous powder layer forms and there are deeper grooves appeared on the friction surface. Too high velocity causes a large amount of the coke powder to be thrown out of the friction interface, the upper and lower sample surfaces direct contact, so the friction coefficient is highest and frictional surface wear seriously.

The above analysis indicates that the powder layer is more likely to form under the higher velocity, so that interfacial friction occurs inside the powder layer, decreasing friction coefficient, and improving friction characteristics of the surface. The powder layer is not easy to form under too high velocity, resulting in higher friction coefficient and serious frictional surface wear.

Table 2. EDS results (wt%) on the surface of the powder layer under different velocities.

| Velocity (m/s) | C   | Fe  | Si  | Total |
|---------------|-----|-----|-----|-------|
| 0.15          | 5.90| 93.33| 0.77| 100.00|
| 0.30          | 8.52| 91.25| 0.23| 100.00|
| 0.40          | 18.55| 81.30| 0.15| 100.00|
| 0.52          | 1.30| 98.70| 0.00| 100.00|

EDS: energy-dispersive X-ray spectrometry.
Effect of load on friction coefficient and powder layer

Friction coefficient. Figure 9 shows when the sliding velocity keeps at 0.40 m/s, the friction coefficient under different load increases. It can be seen that the friction coefficient increases with the increasing load. The main reason for this phenomenon is that under a certain amount of powder, the higher load is not easy to form the powder layer, the lubrication performance of the coke powder is limited, resulting in the increase of the friction coefficient.

Microstructure and elemental proportion of powder layer. Figure 10 shows the SEM micrographs of the powder layer surface under different loads. Table 3 lists the weight percentages of the three main elements C, Fe, and Si on the surface of the powder layer.

As shown in Figure 10(a) and Table 3, the weight proportion of C element is 18.55% on the powder layer surface, forming a compact and complete powder layer. Interfacial shearing mainly occurs inside the powder layer, so the friction coefficient is low.

As shown in Figure 10(b) and Table 3, the weight proportion of the C element on the powder layer surface is 10.89%, forming a thin powder layer. There are more scratches on the powder layer surface due to the effect of abrasive hard particles. Interfacial shearing still mainly occurs inside the powder layer; the powder layer

Figure 8. SEM micrographs of powder layer surface under different sliding velocities: (a) 0.15 m/s, (b) 0.30 m/s, (c) 0.40 m/s, and (d) 0.52 m/s.

Figure 9. The effects of load on friction coefficient.
is thin, and so the coke powder lubrication is limited, and the friction coefficient is high.

As shown in Figure 10(c) and Table 3, the weight proportion of the C element on the powder layer surface is 4.52%, forming a thinner powder layer. Due to the thinner powder layer, the interfacial shearing mainly occurs between the powder particles and the friction surfaces or inside the powder layer, so the friction coefficient is higher. Meanwhile, there are deeper wear grooves on the powder layer surface. It is indicated that the higher load is not conducive to the formation of the powder layer, coke powder lubrication limited, so the friction coefficient is higher.

As shown in Figure 10(d) and Table 3, Due to too high load, a part of powder layer is damaged, direct contact of the upper and lower sample surfaces leads to more wear grooves on the surface along the direction of movement, severe wear occurs on the surface. Moreover, the content of the C element on another part of the powder layer surface is only 1.15%, indicating that the powder layer is very thin. The coke powder lubrication is limited; the interfacial shearing occurs mainly between the powder particles and the friction surfaces. Due to the reason above, the friction coefficient is highest.

The above analysis shows that a certain amount of powder, the higher the load is not easy to form a layer of powder, while too high load is very easy to damage the powder layer and result in the frictional surface wear.

**Conclusion**

This article aims to study the effects of velocity and load on the friction characteristics in coke powder lubrication under the contact state of steel, coke
powder, and refractory brick. Some conclusions are as follows:

1. The graphitization degree of coke powder is 64.05%; furthermore, the coke powder has a certain lubrication characteristic.

2. The load keeps at 5 MPa; the velocity is 0.15, 0.30, and 0.40 m/s, respectively, under higher velocity; the coke powder forms better powder layer and exhibits better lubrication characteristics. When the velocity increases to 0.52 m/s, the continuous powder layer is not formed, so the friction coefficient is higher, the frictional surface wears seriously and results in vibration to occur.

3. The velocity keeps at 0.40 m/s; the load is 5, 10, and 15 MPa, respectively; and powder layer inclines to deteriorate under higher load. When the load increases to 20 MPa, a part of the powder layer is damaged, and severe wear occurs on the surface.

4. When the load is 5 MPa and the velocity is 0.40 m/s, the coke powder exhibits the best lubrication performance, and the friction coefficient of the interface is the lowest.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was supported by Science and Technology Innovation Project of Colleges and Universities in Shanxi Province, China (No. 2020L0608) and Natural Science Foundation of Shanxi Province, China (No. 201901D111300).

ORCID iD
Jin Xiang https://orcid.org/0000-0002-8946-9328

References
1. Kaur RG and Heshmat H. 100 mm diameter self-contained solid/powder lubricated auxiliary bearing operated at 30,000 rpm. Tribol Trans 2002; 45: 76–84.

2. Seong JK, Min HC, Keun HC, et al. Complementary effects of solid lubricants in the automotive brake lining. Tribol Int 2007; 40: 15–20.

3. Reddy NSK and Rao PV. Experimental investigation to study the effect of solid lubricants on cutting forces and surface quality in end milling. Int J Mach Tools Manuf 2006; 46: 189–198.

4. Donnet C and Erdemir A. Solid lubricant coatings: recent developments and future trends. Tribol Lett 2004; 17: 389–397.

5. Ravindran P, Manisekar K and Narayanasamy R. Tribological behaviour of powder metallurgy-processed aluminium hybrid composites with the addition of graphite solid lubricant. Ceram Int 2013; 39: 1169–1182.

6. Li X, Gao Y, Wei S, et al. Dry sliding tribological properties of self-mated couples of B4C-hBN ceramic composites. Ceram Int 2017; 43: 162–166.

7. Li X, Gao Y, Wei S, et al. Tribological behaviors of B4C-hBN ceramic composites used as pins or discs coupled with B4C ceramic under dry sliding condition. Ceram Int 2017; 43: 1578–1583.

8. Li X, Gao Y and Yang Q. Sliding tribological performance of B4C-hBN composite ceramics against AISI 321 steel under distilled water condition. Ceram Int 2017; 43: 14932–14937.

9. Shi XL, Zha WZ and Wang M. Tribological behaviors of NiAl based self-lubricating composites containing different solid lubricants at elevated temperatures. Wear 2014; 310: 1–11.

10. Prabhu TR. Effects of solid lubricants, load and sliding speed on the tribological behavior of silica reinforced composites using design of experiments. Mater Desi 2015; 77: 149–160.

11. Higgs CF, Heshmat CA and Heshmat HS. Comparative evaluation of MoS2 and WS2 as powder lubricants in high speed, multi-padjournal bearings. J Tribol 1999; 121: 625–630.

12. Wang W, Liu X, Xie T, et al. Effects of sliding velocity and normal load on tribological characteristics in powder lubrication. Tribol Lett 2011; 43: 213–219.

13. Wang W, Liu XJ, Liu K, et al. Experimental study on the tribological properties of powder lubrication under plane contact. Tribol Trans 2010; 53: 274–279.

14. Abdullah AA, Arthur DD, Steven JS, et al. Novel tertiary dry solid lubricant on steel surfaces reduces significant friction and wear under high load conditions. Carbon 2017; 123: 7–17.

15. Fei SL, Wu K and Cheng HF. Investigation of temperature of Tuyer coke by XRD. J Chinese Rare Ear Soc 2008; 26: 575–579.

16. Monaghan BJ, Nightingale R and Daly V. Determination of thermal histories of coke in blast furnace through X-ray analysis. Iron Steel 2008; 35: 38–42.

17. Sushil G, Ye ZZ, Riku K, et al. Coke graphitization and degradation across the Tuyere Regions in a blast furnace. Fuel 2013; 113: 77–85.

18. Doo-Won K, Hyun-Sig K and Jandee K. Highly graphitized carbon from non-graphitizable raw material and its formation mechanism based on domain theory. Carbon 2017; 121: 301–308.

19. Feng W, Qin M and Lv P. A three-dimensional nanostructure of graphite intercalated by carbon nanotubes with high cross-plane thermal conductivity and bending strength. Carbon 2014; 77: 1054–1064.

20. Wang W, Liu XJ and Liu K. Surface observations of a powder layer during the damage process under particular lubrication. Wear 2013; 297: 841–848.
21. Wang W, Kong JC and Gu W. Experimental study on macro and micro characteristics of powder lubricant layer in frictional warm interface. *Tribology* 2016; 36: 233–239.

22. Zhou XH, Sun YS and Wei LM. Interface. *Lubr Eng* 2006; 4: 175–178.

23. Descartes S, Godeau C and Berthier Y. Friction and lifetime of a contact lubricated by a solid third body formed from a MoS1.6 coating at low temperature. *Wear* 2015; 330/331: 478–489.