Wear 352-353 (2016) 54–64

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Ultralow friction between cemented carbide and graphite in water using three-step ring-on-ring friction test

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ARTICLE INFO

Article history:
Received 31 October 2015
Received in revised form
26 January 2016
Accepted 1 February 2016
Available online 6 February 2016

Keywords:
Ultralow friction
Graphite
Cemented carbide
Running-in

ABSTRACT

Effect of running-in process on friction behavior of graphite sliding against cemented carbide in deionized water was investigated using a standard tribometer Plint TE92 in a ring-on-ring contact configuration. A stable and ultralow friction coefficient of about 0.003 between graphite and cemented carbide rings was obtained after a three-step friction test method: Step 1 was rapid pre-sliding at standard operating conditions and then the test apparatus was stopped; Step 2 was the accelerated running-in process under higher load and velocity, and the test apparatus was stopped again; The wear particles on the specimen surface were cleaned, and used water was replaced by new water from step 3. According to the measurements of suface microtopography and macrowaviness, surface geometric features in the interface after three-step friction test reached the optimal harmonious state. Variations of friction coefficient with speed and load were also investigated. The ultralow friction mechanism was attributed to the hydrodynamic effect.

1. Introduction

Water lubrication in machines is increasingly applied in various fields because of its advantages over oil, such as greater environmental compatibility, better heat-transfer properties, and potential for ultralow friction [1,2]. However, poor lubrication film formation caused by ultralow viscosity of water adversely affects the friction and wear behavior between water lubrication interfaces. Corrosion caused by water renders most metallic materials unsuitable for water lubrication systems. This limitation restricts the application of water lubrication. Developments in industrial technology have resulted in the production of engineering ceramic [3,4], plastic [5], graphite [6,7] and alloy steel [8,9] with outstanding corrosion resistance that can satisfy various requirements for water lubrication systems. Thus, improving the lubrication state and reducing friction between water lubrication interfaces are crucial to resolve the limited application of water lubricants. These issues have been extensively investigated in the last two decades; and many researchers found that a suitable running-in process can lead to ultralow friction between water and/or water-based lubrication interfaces with a sliding friction coefficient less than 0.01.

Tomizawa and Fischer [10] first observed the very low friction coefficient ($\mu \leq 0.002$) of Si_3N_4 sliding against itself using a ball-on-disk apparatus in water. They inferred that the Si_3N_4 surface becomes extremely smooth during the running-in period because of tribochemical wear, promoting the achievement of hydrodynamic lubrication. Since then, water lubrication of ceramic has drawn increasing attention. Kato and coworkers [11–20] systemically investigated the effect of operation parameters on the ultralow friction coefficient of ceramics, such as Si_3N_4 and SiC, in water lubrication during the running-in process. These parameters include temperature, load, sliding distance, sliding velocity, surface topography, surface roughness, and micropore texture. Friction coefficient as low as $\mu = 0.001$, i.e., nearly zero friction, was also measured. They also attributed the ultralow friction to the combination of boundary lubrication by products of the tribochemical reaction and hydrodynamic lubrication. Jordi et al. [21] verified this hypothesis using a standard integration of Reynolds equations, which were modified to estimate hydrodynamic film thickness, as well as by measuring Stribeck curves of friction versus velocity at several loads. They also determined the critical velocity and load for hydrodynamic lubrication. In addition, some water-based lubricants were discovered. Li et al. [22] mixed phosphoric acid and water, whereas Ma et al. [22] added glycerol and boric acid into water. By contrast, Hartung et al. [24] added ethylene glycol in water. These lubricants allowed Si_3N_4 to easily achieve ultralow friction. Their results showed that the running-in period is indeed less than that of pure water lubrication. These additives accelerate the tribochemical reaction between lubrication interfaces. Moreover, these additives

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http://dx.doi.org/10.1016/j.wear.2016.02.001
0043-1648/

make the lubricants more viscous than pure water, which facilitates the production of the hydrodynamic effect. The aforementioned studies greatly promoted the application of ceramics in sliding bearings, mechanical seals, and other mechanical components for water and/or water-based lubrication [25,26].

The majority of studies on ultralow friction in water and/or water-based lubrication have focused on ceramic materials, especially Si_3N_4 and SiC. These studies, except for the researches of Wang et al. [15–19], were based on the ball-on-disk apparatus with point-to-point contact. Wang et al. employed the ring-on-disk apparatus with surface-to-surface contact configuration, in which the following factors were considered. First, the running-in process can make the ceramic surfaces become extremely smooth because of the tribochemical reaction between the ceramics and water, thereby avoiding surface asperities affecting lubrication film formation. However, surfaces of other materials, such as graphite, plastic, and alloy steel, will become coarser because of mechanical and/or tribochemical wear during the running-in process. Second, ball-on-disk configuration requires low-level form tolerance and position tolerance of components, contrary to surface-to-surface contact configuration, which requires a much higher level for the flatness and parallelism of components. The latter results in increased running-in time and higher cost. However, many thrust bearings and mechanical seals in water lubrication systems are also made of graphite and/or cemented carbide. The friction and wear behaviors of these materials result from surface-to-surface contact. Point-to-point contact configuration remarkably differs from surface-to-surface contact configuration, such as in the running-in period, critical velocity, and load. For surface-contact materials, it is not reasonable to be arbitrarily based on the results of ball-on-disk experiments. However, few studies have investigated graphite, cemented carbide, or other materials that may also be potential candidates to achieve ultralow friction. The effect of the running-in process on the performance of surface-contact materials remains unclear.

Therefore, this study was performed to investigate the effect of the running-in process on the friction behavior of surface-contact graphite sliding against cemented carbide using a ring-on-ring friction test. A three-step test method was proposed to achieve ultralow friction between the graphite and cemented carbide rings. Step 1 was rapid pre-sliding at standard operating conditions and then the test apparatus was stopped. Step 2 was the accelerated running-in process under higher load and velocity, and the test apparatus was stopped again. The wear particles on the specimen surface were cleaned, and used water was replaced by new water from step 3. The test apparatus was restarted, and ultralow friction occurred under standard operating conditions.

2. Experiment

2.1. Specimens

Friction between cemented carbide and graphite rings was tested. Specific structural diagrams of the two rings are shown in Fig. 1. The cemented carbide was fabricated by compacting and sintering powders of WC and Ni in a certain proportion and combined with a binder. Compared with Co-based cemented carbide, Ni-based cemented carbide possesses more excellent chemical corrosion resistance performance. So, in ship and nuclear power fields, Ni-based cemented carbide is often used to manufacture mechanical seals' components of shaft sealing pumps and journal bearings' components of the shield pump. According to the mass fraction of Ni, there were three kinds of Ni-based cemented carbide commonly used: YN6 (Ni 6%), YN8 (Ni 8%) and YN10 (Ni 10%), which were the material trademarks provided by the Ningbo Vulcan Mechanical Seals Manufacturing Co. Ltd. in China. Different Ni contents could result in different mechanical properties of cemented carbide, for example, the more the Ni content, the lower the hardness, but the change extent was not large, the hardness of YN6 was about 1480 HV, and that of YN10 was about 1320 HV. Even so, experimental results showed there was no obvious difference among the three materials in the effect of running-in process on the friction behavior; after the three-step friction test, all of the three materials sliding against graphite could achieve ultralow friction. The tribological mechanism in the interface during running-in process was not discussed in this paper. So, YN10, the mass fraction of Ni equaling to 10%, was just taken for example in this paper, and the other two kinds of Ni-based cemented carbide were also able to repeat the conclusions of this paper.

The matching ring was phenolic resin-impregnated carbon graphite with high strength and hardness and good wear resistance, which was commonly used to manufacture stationary ring of mechanical seals and thrust pad of thrust bearings. The graphite rings were also provided by the above Vulcan Company, and the material trademark was FH42Z5. Due to phenolic resin can dissolve easily in the alkaline solution, the graphite soaked in an ultrasonic bath with NaOH solution for about 30 min each time until the graphite mass basically maintained invariable after dried at a high temperature larger than 100 °C. The measured mass fraction of phenolic resin was about 3.8%. The porosity was measured by using mercury intrusion method with Micromeritics Autopore IV 9500 Series Pore Size Analyzer, and the exerted pressure ranged from 0.2 to 60000 psia. The measured porosity was about 4.3%, and the average pore diameter was about 15.6 nm.

The other mechanical properties of YN10 cemented carbide and FH42Z5 phenolic resin- impregnated carbon graphite are listed in Table 1. And the only solution used in this study was deionized water.

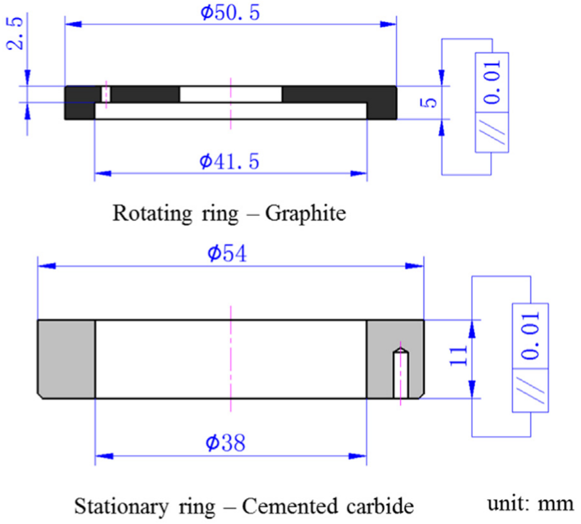

Fig. 1. Structural diagrams of cemented carbide and graphite rings.

Table 1
Physical properties of cemented carbide and graphite.

	Cemented carbide	Graphite
Density (kg m^{-3})	14.6	1.75
Elastic modulus (GPa)	550	18
Hardness	1320 HV	115 HRB
Coefficient of thermal expansion (K^{-1})	5.3×10^{-6}	4.6×10^{-6}
Thermal conductivity (W m^{-1} K^{-1})	92	11
Poisson ratio	0.3	0.25