Available online at www.sciencedirect.com
ScienceDirect
Ceramics International 42 (2016) 3786–3796
CERAMICS INTERNATIONAL
www.elsevier.com/locate/ceramint

Influence of temperature and concentration on tribological properties of silicon nitride in glycerol aqueous solution

Xiaoxue Zhou[a], Bin Lin[a], Shuai Yan[a], Anying Wang[a], Xiaofeng Zhang[a,*], Shidong Ge[b]

[a]Key Laboratory of Advanced Ceramics and Machining Technology of Ministry of Education, Tianjin University, Tianjin 300072, China
[b]Luoyang Bearing Science & Technology Co., Ltd., Luoyang 471039, China

Received 25 August 2015; received in revised form 30 October 2015; accepted 8 November 2015
Available online 27 November 2015

Abstract

Friction and wear behaviors of self-mated Si_3N_4 in glycerol aqueous were investigated by varying the temperature (30 °C, 50 °C, and 70 °C) and concentration (pure water, 5 vol%, 20 vol%, and 50 vol%) of glycerol aqueous solution. Friction tests were conducted on a ball-on-disk apparatus. Normal load and sliding velocity were fixed at 30 N and 0.5 m/s, separately. After each tests, friction coefficients and wear rates were measured to evaluate friction and wear behavior. The results showed that the period of running-in process reduces with the increase of concentration and decrease of temperature. Increase of temperature could intensify wear behavior, and when concentration is larger than 20 vol%, wear rate of glycerol aqueous solution is one order less than that of pure water. Our findings could also guide for the use of glycerol aqueous solution as lubricant at different temperature. At 30 °C, the higher the concentration was, the smaller wear volume and total wear rate were. However, at 50 °C and 70 °C, total wear rates of disk were the largest when concentration is 5 vol%, a concentration of glycerol larger than 20 vol% must be added into water to reduce the wear rate. Wear regimes at different conditions were also given in this paper based on lubrication state number.

Keywords: Ceramics; Running-in process; Glycerol aqueous solution; Wear behaviors

1. Introduction

As one of the most widely used ceramic material, silicon nitride could achieve a very low friction coefficient in water conditions [1]. Besides the advantage of water based lubricant, such as friendly to environment, easy to access, nonflammable and so on [2], it has been widely used as green lubricant to replace mineral oil and even vegetable oil [3]. However, the load carrying ability of water is much smaller than that of oil due to its low viscosity and low pressure–viscosity coefficient [4]. During the past decades, different additives were added into water to increase the load carrying ability and many researchers have conducted a great many tests to investigate the friction and wear behaviors of various water based lubricants.

Hartung Whitney added PLL-g-PEG in aqueous solution [5]. He addressed that due to the absorption of PLL-g-PEG onto the surface of Si_3N_4, lower friction coefficient could achieve at moderate-to-low speeds. However, coefficients of friction of Si_3N_4 in PLL-g-PEG solution are nearly as low as those in water alone.

Besides PLL-g-PEG, there are other additives such as ionic liquids [6,7], alcohol [8,9] and adjusting the pH of the aqueous solution [10]. Tsinghua university [11–16] has found the superlubricity phenomenon based on the lubricant-polyhydroxy alcohol solution mixed with acid solution. They pointed out that the superlubricity is dependent on the total concentration of hydroxyl group in lubricant, which could be affected by the concentration of polyhydroxy alcohol and the number of hydroxyl groups in the

*Corresponding author. Tel./fax: +86 22 27404915.
E-mail address: xijiyu82@163.com (X. Zhang).

http://dx.doi.org/10.1016/j.ceramint.2015.11.040
0272-8842/

molecular structure of polyhydroxy alcohol. Moreover, the number of carbon atoms in the molecular structure has little influence on superlubricity.

Ethylene glycol and its aqueous solution as lubricant have been studied by Zhou [9] and Yan [4]. In Zhou's research, for SiC tribopair, friction coefficient was lowest as the ethylene glycol concentration was 10 vol%. However, in Yan's research, which was also our previous work, he indicated that for Si_3N_4 tribopair, the biggest wear scar diameter was acquired as the concentration of ethylene glycol was 5 vol%. Apart from ethylene glycol, glycerol has been widely used as addition as well. The freezing point of glycerol is 18 °C, which means that pure glycerol is not available in low temperature conditions [17]. However, due to its high viscosity maintenance at high temperature, glycerol could achieve better friction performance than some other water based lubricant. Shi [3] has tested viscosity of glycerol aqueous solution at room temperature (25 °C) and he pointed out that both glycerol and glycerol aqueous solution has provided lower friction coefficient and better anti-wear property than rapeseed oil, which is due to the high viscosity of pure glycerol.

The above researches are all focused on lubricant at room temperature, but few researches have been conducted at high temperature.

Koji Kato [18] has investigated dynamic running-in process of silicon nitride sliding in water at different temperature (20 °C, 50 °C and 80 °C) with a pin-on-disk apparatus. The results showed that the increase of temperature extended the running-in time and obscured running-in process. He also pointed out that wear mode changes from mechanically dominated wear to tribochemically dominated wear as the sliding time increases during the running-in time in water.

Temperature has been shown to have great influence on the viscosity and other parameters of glycerol aqueous solutions. Therefore our research has been focused on the influences of temperature on the tribological performance of glycerol and its aqueous solution. The results could guide for the use of glycerol aqueous solution in different temperatures to reduce the friction coefficient as well as wear rate.

2. Material and methods

Tables 1 and 2 show specimen material and test conditions, respectively. Table 3 shows the Dynamic viscosity for different concentrations of glycerol in water at different temperature. In this study, running-in tests of Si_3N_4 in different concentration of glycerol solutions and in different solution temperatures were conducted on a ball-on-disk tribometer (MMW-200). The tribometer was equipped with thermocouple to alter the temperature of the aqueous solution and to keep the temperature relatively stable ($\pm$ 1 °C). Also in this study, the two chosen variables are solution temperature and volume concentration of glycerol in water. The glycerol aqueous solution used in this study was mixed with deionized water and glycerol, of which the purity was analytical reagent. Volume fractions of pure glycerol in aqueous solution used as lubricant in the tests were 5%, 20% and 50%, respectively. In order to set contrast tests, ball-on-disk tests were also conducted in pure water.

Before the experiments, the Si_3N_4 balls and Si_3N_4 disks were polished and washed with deionized water, then wiped with acetone, finally dried in an oven. The initial roughness of balls and disks were kept at about 14 nm and 20 nm.

During the tests, the ball was submerged in glycerol aqueous solution, of which the temperature was kept constantly at 30 °C, 50 °C and 70 °C separately. Normal load set at the value of 10–50 N is very common in wear test, and normal load is 9.8 N, 14.5 N and 49 N in Ref. [18]. Moreover, if the test wear load is too small then the wear scars will be too small to measure thus relative error in wear scar measurement will impair the test accuracy, and if the test load is too large then overload will lead to severe shake in axe. Considering the test conditions used in Ref. [18] and to make the test results more accurate, we used 30 N as normal load. The ball slid against a stationary ring at a linear speed of 0.5 m/s. For Si_3N_4 ball, its diameter was 9.525 mm. The corresponding contact pressure was e1.7 Gpa according to the Hertz contact theory. For most of the tests, sliding time was set at 3600 s, with the corresponding sliding distant 1800 m, within which tribopair could achieve stationary lubrication state. However, due to the fact that running-in process could not finish in 3600 s when the ball-on-disk test was conducted in pure water at 70 °C, the

Table 1
Material parameters of Si_3N_4 ball and disk.

Material parameters	Ball	Disk
Density (g/cm^3)	3.25	3.27
Lexural strenghth (MPa)	900	791
Vicker hardness (Hv)	1580	1420
Fracture toughness (MPa m$^{1/2}$)	6.0	6.18
Initial roughness	0.014	0.010

Table 2
Test conditions of Si_3N_4 ball-on-disk tribological tests.

Sliding velocity (m/s)	Normal load (N)	Solution temperature (°C)	Volume percentage of glycerol in water (vol%)
0.5	30	30/50/70	0/5/20/50

Table 3
Dynamic viscosity for different concentrations of glycerol in water at different temperature.

Concentration of glycerol in water (vol%)	Dynamic viscosity (mPa s)		
	30 °C	50 °C	70 °C
0	0.80	0.55	0.41
5	0.93	0.63	0.46
20	1.52	0.98	0.69
50	5.72	3.06	1.89