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EFFECT OF WATER TEMPERATURE ON THE ULTRA LOW FRICTION COEFFICIENT OF Si_3N_4–Al_2O_3 SLIDING PAIR[1]

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Abstract
The effect of water temperature on the wear and friction coefficient between a Si_3N_4 ball and a Al_2O_3 disc was evaluated in a ball-on-disc setup,at a sliding speed of 1 m/s, with 54 N load and lubricated with distilled and deionized water. The coefficient of friction in the steady state was 0.02 and 0.006 for water temperatures of 2.6 and 21.5 ºC respectively. For water temperature of 41.1 ºC the friction coefficient did not reach a steady state reaching 0.18 at the end of the test. There was an increase in the wear and also in the running in period as the water temperature was increased. The wear on the alumina disc was smaller than in the silicon nitride ball. After the tests with water temperature of 21.5 ºC the disc has greater roughness than initial value in some sections of the track, besides that ultra low friction coefficient was achieved.
Key words: Friction coefficient; Silicon nitride; Alumina.

EFEITO DA TEMPERATURA DA ÁGUA NO ULTRA BAIXO COEFICIENTE DE ATRITO NO DESLIZAMENTO DO PAR Al_2O_3-Si_3N_4

Resumo
Foram realizados ensaios tribológicos na configuração esfera contra disco, sendo esfera de Si_3N_4 e disco de Al_2O_3, com velocidade de deslizamento de 1 m/s, carga de 54 N lubrificado com água destilada e deionizada, avaliar o efeito da temperatura da água no desgaste e no coeficiente de atrito. O coeficiente de atrito no regime estacionário foi de 0,02 e 0,006 para temperatura da água de 2,6 e 21,5 ºC respectivamente. Para temperatura da água de 41,1 ºC o coeficiente de atrito não atingiu um regime estacionário apresentando um valor de 0,18 no final do ensaio. Foi verificado um aumento no desgaste bem como no tempo de running in com o aumento da temperatura da água. O desgaste no disco de alumina foi menor que na esfera de nitreto de silício. Após os ensaios com temperatura da água de 21,5 ºC, onde foi obtido o regime de ultra baixo coeficiente de atrito, o disco apresentou uma rugosidade com valores acima da inicial em alguns trechos da trilha obtendo-se mesmo assim ultra baixo coeficiente de atrito.
Palavras-chave: Coeficiente de atrito; Nitreto de silício; Alumina.

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1 INTRODUCTION

The tribological behavior of ceramics under water lubrication has been investigated by several authors. Anderson[(1)] observed that for alumina the kinetic friction coefficient is 0.2 in steady state. He also observed that for silicon carbide μ = 0.02. The tribological behavior of silicon nitride sliding on itself, using gas as a interfacial medium, been studied by Tomizawa and Fischer,[(2)] who showed that the friction coefficient of this pair is lowest in humid gas, when compared with dry air or dry nitrogen. They obtained the friction coefficient of μ = 0.85 in Argon and Nitrogen, dry (0% relative humidity), μ = 0.80 in dry air and oxygen (0% relative humidity), μ = 0.75 in argon with relative humidity of 95%, μ = 0.70 in water-rich atmosphere. They attributed this to the occurrence of tribochemical reactions in the process that, according to these authors, would have led to the formation of a tribofilm composed of silicon dioxide with low shear strength.

Tomizawa and Fischer[(3)] discovered that the friction coefficient of silicon nitride sliding against itself, with water as lubricant, evolved from a starting value of 0.7 and reached values as low as 0.002. They attributed the very low values of the friction coefficient to the formation of a highly polished surfaces among the bodies. They observed also that a similar phenomenon occurred with SiC-SiC pair. After they, several authors obtained similar values for the friction coefficient .

Recently, Ferreira[(4)] discovered that ULFC can be obtained for the pair Si_3N_4–Al_2O_3 sliding in water. In his work, Ferreira showed that the decrease in surface roughness decreases the time of running-in, which was in agreement with the result Tomizawa and Fischer.

However, the mechanism for ULFC occurrence is not well understood. Some authors attribute the phenomenon to the hydrodynamic lubrication,[(2-6)] others considered that a tribo reaction is necessary to establish the ULFC regime and that the lubrication occurred in the mixed regime.[(7,8)] All those studies were performed with SiC-SiC ou Si_3N_4–Si_3N_4 pair. Ferreira[(4)] adopted the later mechanisms to explain the ULFC regime to the Si_3N_4-Al_2O_3 sliding under water with friction coefficient in the range from 0.002 to 0.004.

It was attributed in all the studies above mentioned that water plays a key role. The effect of the water temperature was studied for SiC-SiC pair under sliding conditions.[(9)] It was established that the increase of the water temperature leaded to an increase of wear and friction coefficient in mated SiC-SiC. This paper studies the effect of the water temperature for the unmated Si_3N_4-Al_2O_3 pair lubricated by water on the tribological behavior of this ceramic pair.

2 EXPERIMENTAL

A high purity alumina powder with 750 ppm MgO (AKS-3030A, Sumitomo Chemical Co., Japan) was uniaxially pressed to form discs in a cylindrical die (diameter of 52 mm) at 45 MPa. The discs were then pressed at 200 MPa in a cold isostatic press and afterward sintered at 1650 ^{o}C for 1h in air using an electric furnace.

The flat surfaces of sintered discs were machined and then a hole in the center of each disc was drilled to fix it at the wear equipment. Before the wear test, the flat surfaces were lapped using copper lapping discs and a 15 μm diamond suspension. The value of RMS roughness was 350 nm, evaluated by contact profilometer (Kosaka, Surfcorder - 1700α).

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Lubricated sliding wear tests were conducted using a ball-on-disc configuration in the Plint TE67 equipment. Commercial Si_3N_4 bearing balls with 11.11 mm (7/16") in diameter were used in the tests. During the test, the prepared Al_2O_3 discs with diameter of 51 mm and thickness of 6.5 mm were rotated with a wear track tangential speed of 1.0 m/s (562 rpm). The Si_3N_4 ball was pressed against the Al_2O_3 disc through a dead weight system with a normal load of 54.25 ± 0.17 N that resulted in a mean Hertzian pressure of 900 MPa. The tests were performed at constant temperatures of 2.6, 21.5 and 41.1± 1 ºC with a flux of distilled and deionized water (18.2 MΩ.m, Millipore milli-Q system) that covered the contact interface between ball and disc. The friction force was monitored with a cell load with an accuracy of 0.10 N at a frequency of 1 Hz. The mean friction force (and friction coefficient) was measured up to achieve at least 10 min at the ultra low friction regime. Five tests were carried out to confirm the reproducibility of the results.

The specimens were cleaned in an ultrasound bath (20 min in acetone) before and after the tests. The roughness profiles were measured before and after the tests without filtering for comparative purposes. The worn surfaces of tested ball and disc were analyzed by optical microscopy.

Table 1 shows the measured physical and mechanical properties of tested materials.

Table 1: Physical and mechanical properties of Al_2O_3 disc and Si_3N_4 ball

Material	Alumina	Silicon nitride
Density, ρ [g.cm^{-3}]	3.96	3.26
Vickers Hardness, HV_{10} [GPa]	16.3	14.6
Young Modulus, E [GPa]	403	316
Frature Toughness, K_{Ic} [MPa.m$^{1/2}$]	3.5	5.9

3 RESULTS AND DISCUSSION

3.1 Tribological Tests

A typical plot of tribological tests showing the friction coefficient as a function of sliding time is shown in Figure 2.

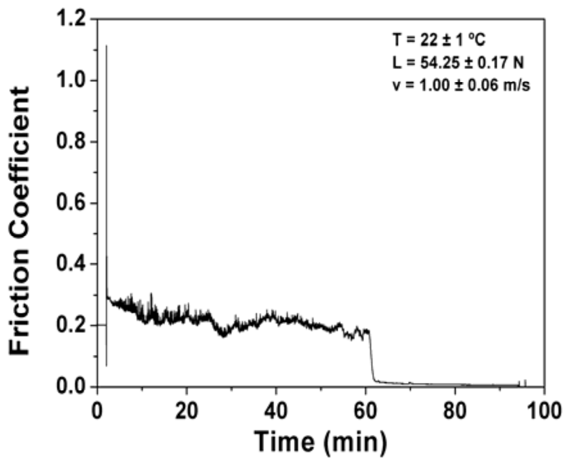

Figure 2: Si_3N_4-Al_2O_3 friction coefficient lubricated with water. T - water temperature, L - applied load, v - sliding speed.

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At the beginning of the test, the friction coefficient reached 1.5 and after a short period, decreased to 0.3. Then it was followed a transient regime where the friction coefficient variation was large. During this period the mean value and the amplitude of the friction coefficient decreased and after one hour the friction coefficient reached values of 0.006 remaining in this regime until the test was ended. This friction coefficient range (<0.01) were named Ultra Low Friction Coefficient range.

Figure 3 shows the friction coefficient vs time for the tests performed at constant temperatures of 2.6; 21.5 and 41.1ºC.

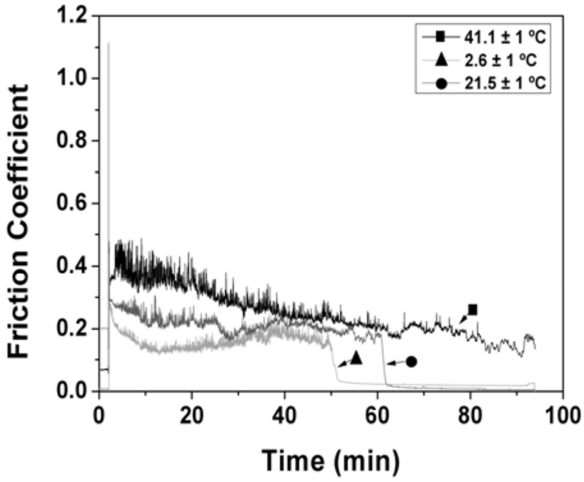

Figure 3: Friction coefficient versus sliding time, for Si_3N_4-Al_2O_3. Water. Constant temperature.

For the tests performed with water at 2.6 ºC, after the first friction spike, the friction reached 0.45, decreased up to 0.2, following a period where the friction coefficient variation was large and after fifty minutes the friction curve became smooth and the friction coefficient decreased to 0.02, a value above the ULFC boundary of 0.01. For the test performed with water at 21.5 ºC, the friction coefficient behave the same way as above and after about one hour reached the ULFC regime with friction coefficient of 0.006.

For tests performed with water at 41.1 ºC, the friction coefficient exhibited a larger transient regime where the mean value and the variation of the friction coefficient decreased with the time. However, there is no a smooth region in the friction curve as observed in the tests performed at lower water temperatures. At the end of the tests the friction coefficient reached a value of 0.18.

Figure 4 shows typical worn surfaces on the disks and the plateau formed on the Si_3N_4 ball, as well as the roughness profiles.

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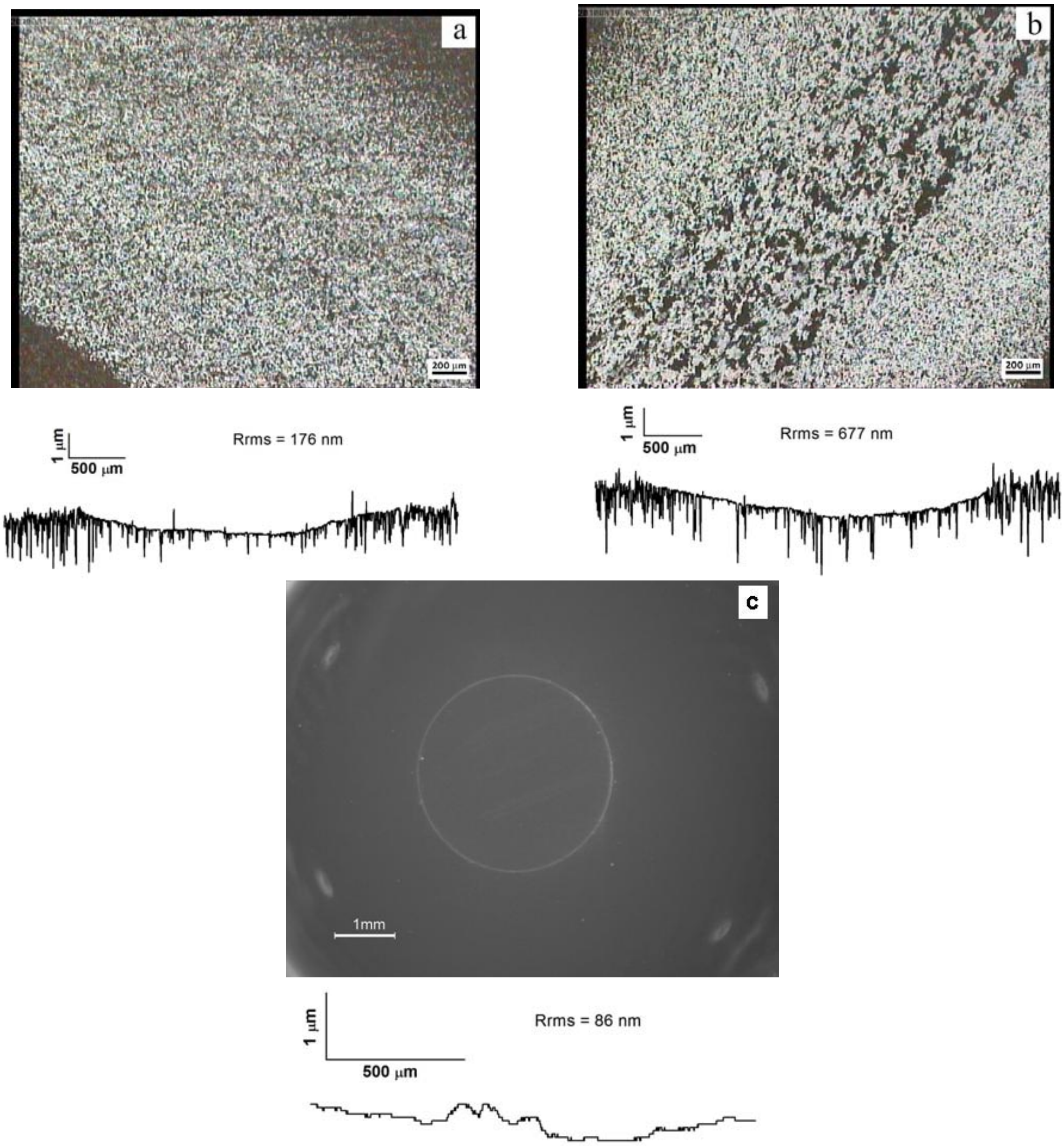

Figure 4: a and b disc wear tracks, c plateau on the ball with their respective roughness profiles.

It was observed that the wear track on the discs where not uniform, as shown in figures a and b. In some regions, like in figure 4a, the rms roughness decreased during the tests and in regions like if figure 4b the rms roughness reached values about twice the roughness at the beginning of the test. This behaviour could not be explained. The ball wear was in all tests uniform and the roughness was always lower than that of the discs.

Figure 5 summarizes the wear of the Si_3N_4-Al2O3 pair materials as a function of the water temperature. The wear of both materials increased with increasing the water temperature and the wear of the discs was lower than the wear of the balls. The worn volume of the alumina discs were 29%, 26% e 16% of the worn volume of the silicon nitride balls as the test temperatures were changed from 2.6 to 21.5 and to 41.1 ºC. It was also noticed that the wear response of the Al_2O_3 disc and the Si_3N_4 ball was similar when the test temperature was increased from 2.6 to 21.5 ºC. As the

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test temperature was increased from 21.5 to 41.1 ºC the wear of the Si_3N_4 ball was greater than the Al_2O_3 disc.

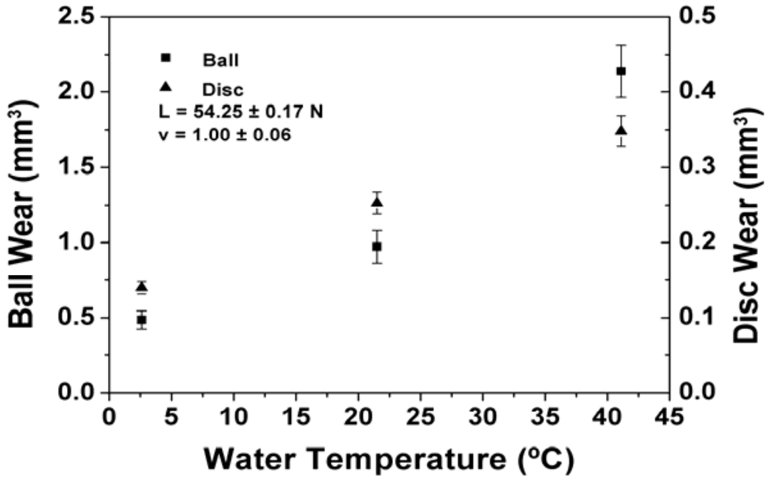

Figure 5: Wear volume versus water test temperature.

Table summarizes the friction coefficient at the end of the tests of the Si_3N_4-Al_2O_3 pair as well as the running-in time of the non steady state friction regime as a function of the water temperature.

Table 2: Friction coefficient at the end of the tests and running-in time of the non steady state for the tests at controlled water temperature

Water temperature (ºC)	Friction coefficient	Running-in time (min)
2.6	0.02	50
21.5	0.006	65
41.1	0.18	>90

The lowest friction coefficient was measured at the test performed at 21.5 ºC suggesting that the wear behavior was not controlled by the friction coefficient at the end of the test. It is more likely that was the non steady state friction regime length that controlled the wear behavior.

According to the literature(3,4,5,7) it is necessary that a smooth surface on the wear track in order that a ULFC regime was achieved. As it can be seen in Figure 4b the smoothening of the wear track did not occur and besides that, at 21.5ºC the ULFC regime was achieved. This result suggests that the current explanation for the ULFC regime needs to be revised. The increase in the friction coefficient from 0.006 to 0.02 as the test temperature was changed from 25.1 to 2.6 ºC may be atributed to the increase in water viscosity. For pure water the viscosity increases from 0.9 to 1.6 10^{-3} Pa.s as the temperature decreases from 25.1 to 2.6 ºC and this may led to an increase in the friction coefficient according to the well know Stribeck curve once both samples run free from mechanical contact as indicated by the smooth friction curves.

The ULFC was not achieved in the test performed at 41.1 ºC. The friction curve (Figure 3) shows an erratic behavior of the friction coefficient that is typical of dry sliding besides the fact that the wear of the Si_3N_4 ball was the greatest among the tests providing more silica to the interface than for the test performed at 25.1 ºC.

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Besides that the ULFC was not achieved. An explanation to be checked by means proper measurement of the silica-water fluid is that the decrease in the water viscosity prevailed upon the increase in the plateau area of the Si_3N_4 ball and this wear pair did not achieved the hydrodynamic regime.

5 CONCLUSION

Ultra low friction coefficient (ULFC) was reached in an unmated Si_3N_4-Al_2O_3 sliding pair under water. This result showed that the ULFC is not a phenomenon exclusive of Si_3N_4 - Si_3N_4 and SiC-SiC mated pairs as was first observed by Ferreira 2008.

The ULFC was obtained without a very smooth interface as pointed out by the literature.

It was observed that the temperature plays a key role either in the friction coefficient running in length as well as in the value of the friction coefficient in the ULFC regime when it was achieved and that the greater the test temperature the greater the wear of the sliding pair.

The tribological behaviour was atributed to the effect of the water viscosity but the measurement of the fluid viscosity (water + tribowear debris) or other physicochemical properties are necessary in order to elucidate the phenomenon.

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