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Influence of surface wettability on friction and wear tests

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Abstract

In this work the effect of surface wettability of different materials on friction and wear behaviour with sliding friction of 100% has been studied. The following materials have been chosen: AISI 1050 and AISI 420 steels, pyrex glass, teflon (PTFE) and carbon fiber. All have different surface wettability angles (θ). Tests with these materials have been carried out with a pin-on-disc tribometer with homogeneous and heterogeneous couplings in dry conditions and with oil and water lubrication. The most important result achieved with the mechanical tests and the SEM examinations is that with couplings of a hydrophillic and a hydrophobic material, water lubrication has a greatly positive effect. Particularly with hydrophobic discs and hydrophillic pins the friction factor and the wear have been lower than those with oil lubrication. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Wettability; Hydrophobic; Hydrophillic; Lubrication

1. Introduction

In this work the authors investigate the possibility of a rational use of water-based lubricants to solve tribological problems.

Even if until now it was thought that it is impossible that water could produce a continuous fluid-film capable of carrying loads between two sliding surfaces due to its low viscosity, the study of water lubrication is not completely new [1].

The behaviour of water-lubricated ceramic journal bearings has been studied [2]. The obtained results suggest to extend water lubrication to systems already working in water like submerged pumps.

Encouraging results of water lubrication have been achieved with couplings of polymeric materials against steels [3]: experimental utilization of water-based lubricant (95% water, 5% oil), has been proposed for drills, rock drills and drifters in mines.

The effect of chemical hydrophobic and hydrophillic groups in water-based lubricant with different surface-active agents as lubricant additives, has been investigated for couplings of steels, polymers and glass [4]. In the case of water with surface-active agents as additive, the friction factor is similar to the one obtained with oil; the friction factor is even lower when this kind of lubrication is applied to glass surfaces.

At present there are several practical applications of water lubrication:

- artificial skating rinks instead of those of ice. They are made of hydrophobic polymeric material and the blades of the ice-skates slide with low friction coefficient thanks to the water lubrication.
- skis with teflon coating lubricated by the water which is produced by the contact pressure on the snow;
- submerged pumps and journal bearings of rolling-mills.

Food and pharmaceutical industries are demanding for the substitution of traditional oils with water-based lubricants because of the pollution of their products caused by their machinery.

2. Materials used and tests methodology

2.1. Materials

Five materials have been tested:

1. AISI 1050 steel
2. AISI 420 steel

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Table 1
Chemical composition of the two steels (wt.% Fe bal.)

Material	C	Cr	Mn	Si	P	S
AISI 420	0.38	14	0.95	1.25	0.04	0.03
AISI 1050	0.5	/	0.60	0.25	0.035	0.035

3. commercial polytetrafluoroethylene (PTFE)
4. pyrex glass
5. carbon fiber ribbon in polymeric matrix (HY-1534, the epoxy resin 934 fiberite).

Chemical composition of the two steels and mechanical characteristics of all the tested materials are shown in Tables 1 and 2.

The parameter which characterizes the surfaces, that we deemed essential, is the surface wettability [5–7], measured by the contact angle θ. This is defined as the angle that the tangent to the drop plane makes with the surface plane, in stable equilibrium conditions. The contact angle characterizes the surfaces of different materials and they are defined wettable (highly hydrophillic $0° \leq \theta \leq 45°$) or not wettable (highly hydrophobic $90° \leq \theta \leq 180°$), as shown in Table 3.

Roughness of the discs surfaces are shown in Table 4: R_a and R_m have been measured by a surface roughness analyzer (Hommelwerke), according to ISO and DIN Standard.

2.2. Tests methodology

Using the five materials two types of couplings have been tested:

(a) all the possible homogeneous couplings (pin and disc of the same material)

(b) all the possible heterogeneous couplings (pin and disc of different material). In these cases pin and disc have been swapped.

All the specimens, after washing with acetone [8], were tested in air with pin-on-disc tribometer, in the three following conditions:

- dry
- water lubrication
- oil lubrication

Table 2
Mechanical characteristics of the tested material

Material	R (MPa)	R_s (MPa)	Hardness HV (kg/mm^2)
AISI 1050 steel	770	550	230
AISI 420 steel	800	600	245
PTFE	31	26	40
Pyrex glass	83	80,7	305
Carbon fiber	2600	2600	316

Table 3
Wettability characteristic of the tested material

Material	Contact angle θ	Wettability characteristic
Pyrex glass	0°	highly hydrophilic
AISI 1050 steel	40°	highly hydrophilic
AISI 420 steel	50°	basically hydrophobic
Carbon fiber	96°	highly hydrophobic
PTFE	126°	highly hydrophobic

Table 5 shows the operational conditions that remained constant with all the test types.

Pin-on-disc tribometer allows one to know the friction force which opposes motion and the wear, this last one is measured by the deepness of the wear track on the disc. The wear is measured in millimeters. In the case of a pin very much harder than the disc, this value measures the deepness of the wear track on the disc: In all the other cases the value measures the wear of both pin and disc. In both cases the authors have verified that the friction factor is not affected if the harder material is the pin or the disc.

3. Results

Sixty different tests were carried out and they were repeated three times each. To ensure reproducibility every test was repeated three times. In Table 6 are shown friction factors and wear values for each tests after 10,000 cycles.

The results are divided in three sets:

1. couplings with both hydrophillic surfaces materials
2. couplings with both hydrophobic surfaces materials
3. couplings with one hydrophillic surface material and the other one with hydrophobic surface.

Looking at the values of Table 6 the following can be noted.

(I) couplings hydrophillic/hydrophillic. In all these couplings the values of wear and friction factor are very high with no lubricant, low with water and very low with oil.

Generally speaking it has been noted a very low lubrication effect of water: the wear and the friction factor are lower than in the dry case and this is probably due to the

Table 4
Roughness of the discs surfaces

Disc material	R_a (μm)	R_m (μm)
AISI 1050 steel	0.3	4.3
AISI 420 steel	0.2	2.5
PTFE	0.5	13.4
Pyrex glass	0.08	1.2
Carbon fiber	4	28

Table 5
Operational conditions of the tests

System geometry	Sphere on disc
Geometry and dimensions of the specimens	disc: Cylinder ring 40 mm external diameter, 24 mm, internal diameter, height 8 mm pin: half sphere 10 mm diameter
Sliding friction	100%
Angular speed	≅ 100 rpm
Max number of rounds	10,000
Normal load	20 N
Solvent to digrease pin and disc	acetone
Lubrication	continuous dropping of lubricant
Lubricants	- oil for manual gear box ZC 90 SAE 80W-90 - demineralized water

fact that the surfaces, as they are wettable, allow the permanence of a very thin layer of water (the only exception is the glass/glass coupling).

Fig. 1a and b show that water supply in the homogeneous coupling with the hydrophillic steel AISI 1050 does not allow the seizure, which on the contrary, very soon happens in dry condition, even if with a wear and a friction factor very much larger than those with oil.

More specifically Fig. 1b shows that the friction factor initially is very low then after a little time, it becomes steady with a very high value because the coupling cannot maintain a water film.

(II) couplings hydrophobic/hydrophobic. With all these couplings the values of the wear and of friction factor are very high in dry condition, slightly lower than in the former case with water and very low with oil.

Adding water does not improve the tribological performances of the dry condition. As a matter of fact the hydrophobic surfaces do not allow the permanence of a film of water.

Table 6
Summary of the results of all the tests after 10,000 cycles

Disc	Pin	Friction factor after 10,000 rounds			Wear (mm) after 10,000 rounds		
		Lubrication			Lubrication		
		Dry	Water	Oil	Dry	Water	Oil
Hydrophilic / hydrophilic couplings							
AISI 1050	AISI 1050	seized	0.43	0.16	seized	0.08	0.01
GLASS	GLASS	seized	seized	0.07	seized	seized	0.01
AISI 1050	GLASS	0.76	0.55	0.17	0.04	0.11	0.02
GLASS	AISI	0.9	0.49	0.09	0.1	0.09	0.02
Hydrophobic / hydrophobic couplings							
PTFE	PTFE	0.31	0.22	0.09	0.31	0.41	0.07
AISI 420	AISI 420	seized	seized	0.16	seized	seized	0.03
AISI 420	PTFE	0.23	0.2	0.05	0.62	0.62	0
PTFE	AISI 420	0.21	0.16	0.13	0.08	0.08	0.01
C. FIBER	AISI 420	0.19	0.25	0.11	0.02	0.23	0.18
C. FIBER	PTFE	0.07	0.21	0.06	1.34	0.1	0.06
Hydrophobic / hydrophilic couplings							
AISI 1050	PTFE	0.2	0.19	0.11	0.96	0.89	0.08
PTFE	AISI 1050	0.21	0.13	0.18	0.08	0.04	0.05
PTFE	GLASS	0.21	0.03	0.18	0.06	0.02	0.03
GLASS	PTFE	0.27	0.09	0.01	0.45	0.05	0.02
AISI 1050	AISI 420	seized	0.49	0.12	seized	0.04	0.01
AISI 420	AISI 1050	seized	0.4	0.1	seized	0.22	0.03
AISI 420	GLASS	0.66	0.56	0.07	0.72	0.45	0.02
GLASS	AISI 420	seized	seized	0.15	seized	seized	0.01
C. FIBER	AISI 1050	0.21	0.08	0.2	0.17	0.01	0.02
C. FIBER	GLASS	0.28	0.05	0.13	0.02	0.01	0.03

Seized: means that the vibrations of the system were so high that the test has been immediately interrupted.

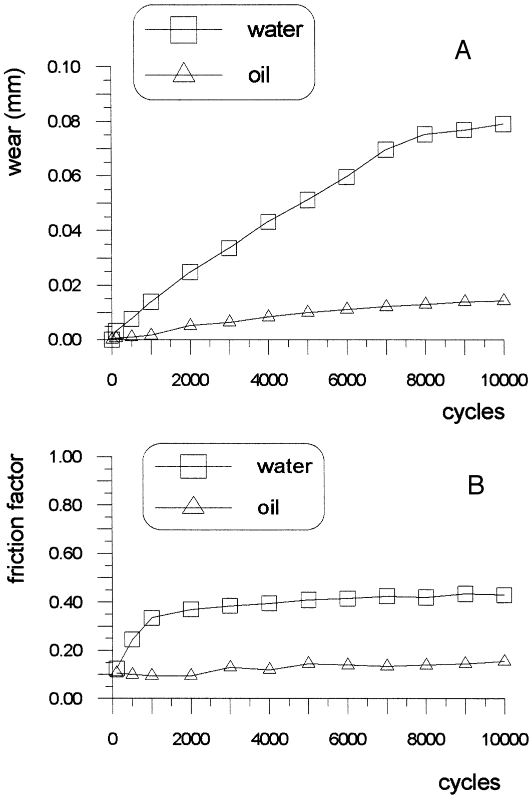

Fig. 1. a–b. Wear and friction factor vs. cycles for AISI 1050 pin/AISI 1050 disc hydrophilic/hydrophilic: water and oil lubrication. With no lubricant this coupling seized.

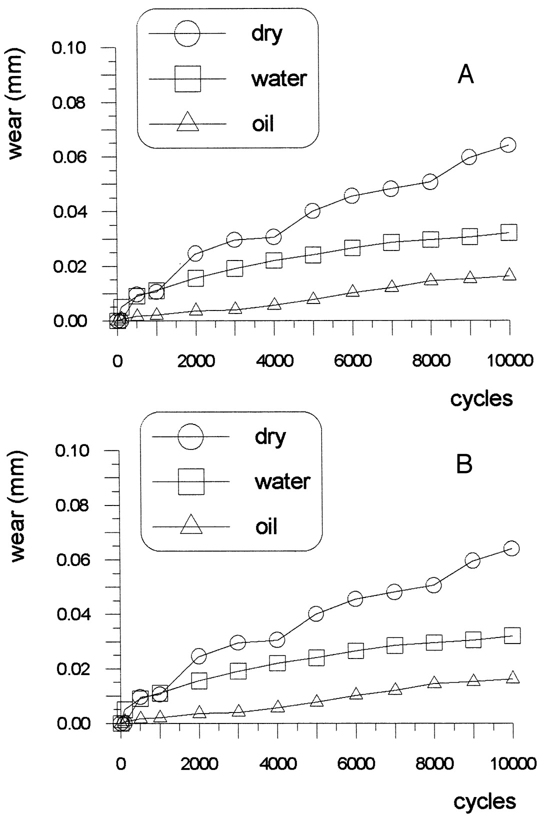

Fig. 2. a–b. Wear and friction factor vs. cycles for glass pin/PTFE disc hydrophilic/hydrophobic: water and oil lubrication and dry condition.

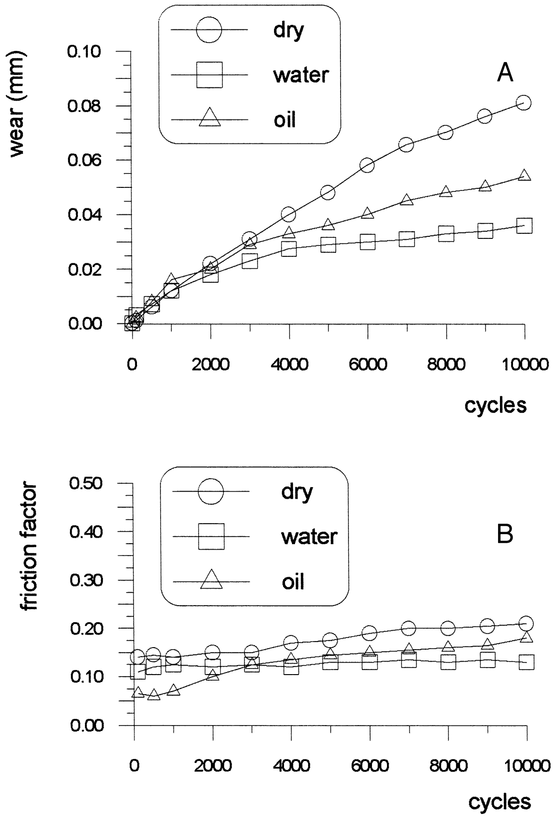

Fig. 3. a–b. Wear and friction factor vs. cycles for AISI 1050 pin/PTFE disc hydrophilic/hydrophobic: water and oil lubrication and dry condition.

(III) couplings hydrophobic/hydrophillic. In these cases the influence of the different surface wettability of the sliding members has been noted.

Two cases have been verified.

(a) Hydrophobic disc and hydrophillic pin. The water has shown a very good lubrication capability. Actually in all these four couplings the wear and the friction factor with water are very low as shown in Figs. 2–5. Figs. 2–5 show, that in the couplings glass pin/PTFE disc, AISI 1050 pin/PTFE disc, AISI 1050 pin/carbon fiber disc, glass pin/carbon fiber disc respectively the wear and the friction factor with water are lower than those with oil. The most evident differences are in the glass pin/carbon fiber disc case; in this case the wear with oil is higher than those in dry condition. In this case the oil can not lubricate the system, this is due also to the fact that carbon fiber is oil repellent, so the oil film oil on the disc can be easily broken through.

(b) Hydrophillic disc and hydrophobic pin. In these couplings the water lubrication is not very effective.

Actually with water there is a lowering of wear and friction factor with respect to the dry case but wear and friction still remain higher than those achieved with oil.

4. Discussion

The results of the mechanical tests, confirmed by the SEM analysis, clearly show that the surface wettability of the materials has an effect in tribological tests.

The different surface wettability causes a different distribution of the drops of water on the pin and on the disc as schematically shown in Figs. 6–9.

In the couplings between pin and disc, the possibility to have a lubricant layer of water depends on the short range polar forces (Van der Waals dispersion forces), between the molecules of water and the surfaces of the materials.

In Figs. 10–13 is shown a possible model to explain the possibility to have a water layer between the four different kinds of couplings.

When the surfaces of pin and disc are hydrophillic, it has been noted that the layer of water, which was initially on the disc has been immediately taken away.

In Fig. 10 is shown a drawing of this case. The same affinity for water of the pin and of the disc makes the layer very thin. So in this case the water does not make a layer which is capable of hydrostatic lift but still lubricates as an adhesive layer.

In fact this thin layer prevents seizing in the homogeneous coupling of AISI 1050 steel, while seizure happens in the dry condition, as shown in Table 6.

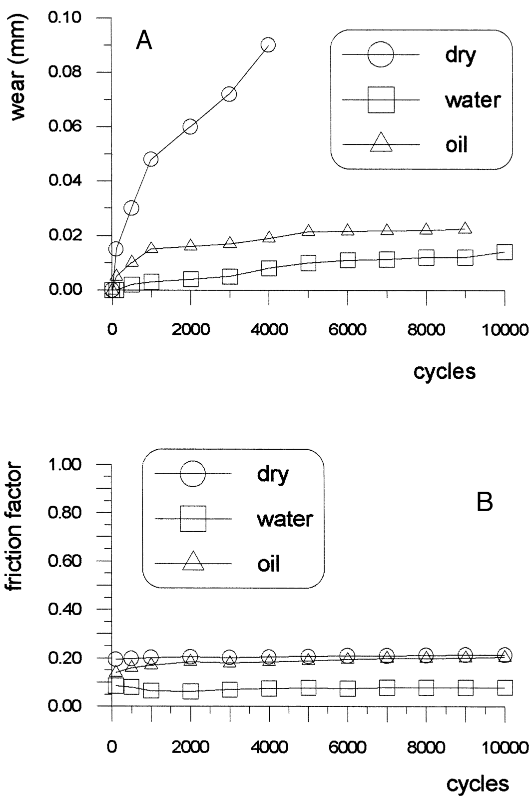

Fig. 4. a–b. Wear and friction factor vs. cycles for AISI 1050 pin/carbon fiber disc hydrophilic/hydrophobic: water and oil lubrication and dry condition.

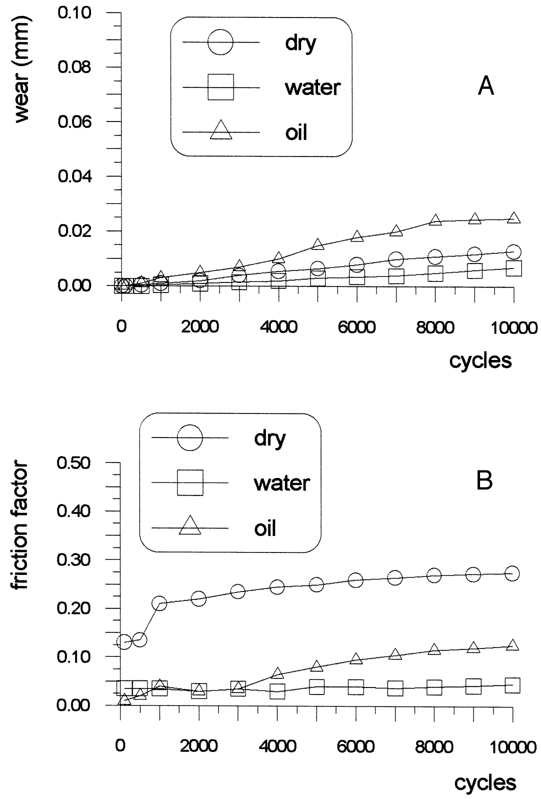

Fig. 5. a–b. Wear and friction factor vs. cycles for glass/carbon fiber disc pin hydrophilic/hydrophobic: water and oil lubrication and dry condition.

When the surfaces of pin and disc are both hydrophobic, it has been noted that there is no formation of any layer of water between the surfaces. Fig. 11 shows a model of this case.

The results of the mechanical tests show that in this coupling the water has no lubricating effect.

When the surfaces of pin and disc have different wettability characteristics the mechanical tests have shown that water has lubricant capability.

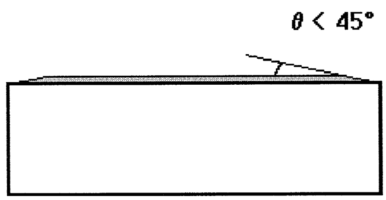

Fig. 6. Shape of a drop of water on an hydrophilic disc.

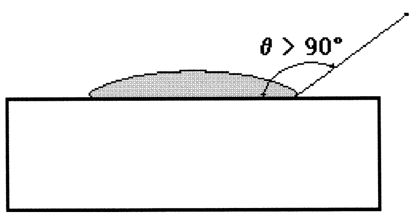

Fig. 7. Shape of a drop of water on an hydrophobic disc.

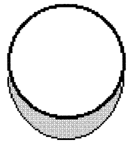

Fig. 8. Shape of a drop of water on an hydrophilic pin.

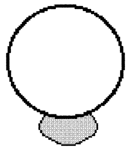

Fig. 9. Shape of a drop of water on an hydrophobic pin.

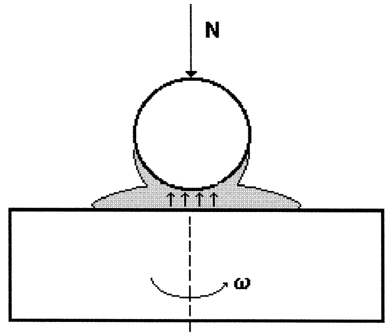

Fig. 12. Hydrophobic disc with hydrophilic pin, lubricated with water.

Particularly, in every couplings with a *very hydrophobic disc*, and with a *very hydrophillic pin*, a continuous layer of water has been established between pin and disc, with good effects on lubrication as shown in Figs. 2–5. Evidence of this fact is given by the micrograph of Figs. 14 and 15, in which the resulting surface wear produced by a hydrophillic pin in contact with a hydrophobic disk is shown. Comparing the pin (AISI 1050) against the disk (carbon fiber), water lubricated, shown in Fig. 14 a–b and oil lubricated shown in Fig. 15 a–b it is easy to note that:

(a) the track produced on the carbon fiber with water lubrication is less deep then the one produced with oil.

(b) there is a protective layer made of oxide and carbon particles as shown by an EDS analysis on the pin with water lubrication. And yet the pin with oil lubrication suffered a remarkable wear as shown in Fig. 15b.

Another confirmation of the behaviour of the water is the coupling between the disk of PTFE and the pin of AISI 1050 in which the width of the track with water lubrication is 0.8 mm average and with oil is average 1.5 mm as shown in Figs. 16 and 17.

Another effect due to the water is its capability to *wash the surfaces*, that is the fact that water, instead of oil, rapidly removes the wear debris. This behaviour contributes to the good tribological performances of these couplings. As it was seen during the tests, in the case of the former coupling (AISI 1050 pin/PTFE disc) the debris, with water lubrication, were thrown out during the motion and were collected on the surface of the testing machine chamber, while with oil lubrication the debris remained on the track.

The model shown in Fig. 12 explains that the presence of the layer is not due to the low viscosity of the water, but to the different wettability of the materials: the hydrophobic disc, which tries to drive out water and the hydrophillic pin which tries to become wet.

The hydrophobic surface of the disc against the hydrophillic surface of the pin promotes the formation of a layer of water which has hydrostatic lift. This phenomenon greatly reduces the contacts between the sliding surfaces. This fact is confirmed by the SEM observations: within the same coupling, actually the wear track on the surface of

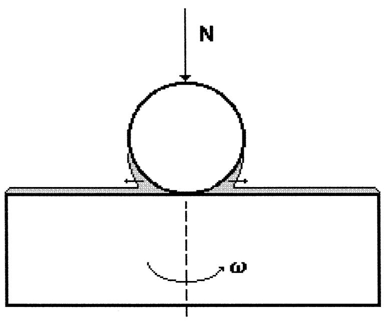

Fig. 10. Hydrophilic disc with hydrophilic pin, lubricated with water.

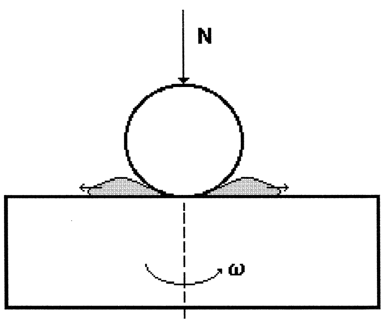

Fig. 11. Hydrophobic disc with hydrophobic pin, lubricated with water.

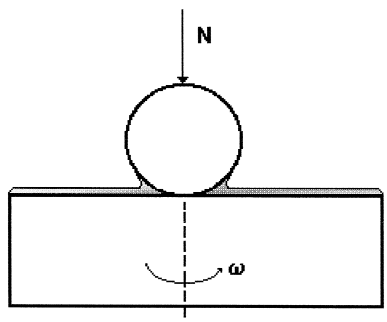

Fig. 13. Hydrophilic disc with hydrophobic pin, lubricated with water.

In order to have an efficient water lubrication it is not only necessary that pin and disc have very much different wettability, but also the geometric disposition is important.

Fig. 13 shows the case of a hydrophobic pin with a hydrophillic disc with water. In these cases the repulsion

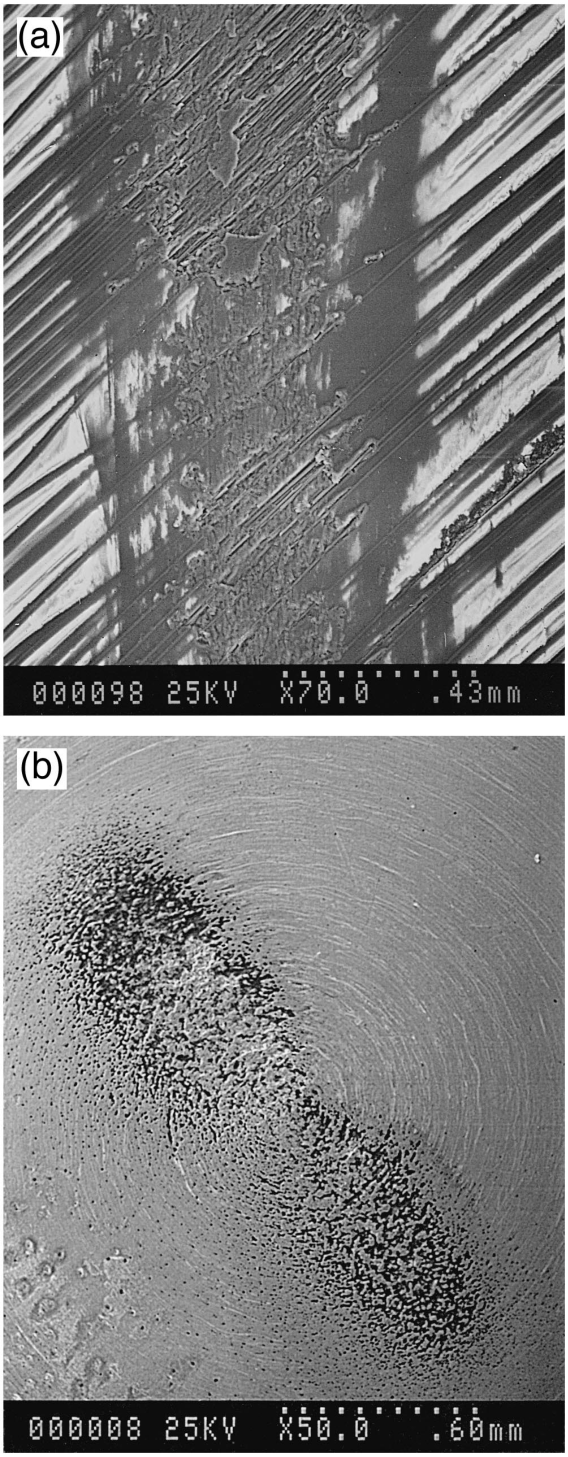

Fig. 14. a. Carbon fiber disc surface after the test against AISI 1050 pin, water lubricated. b. AISI 1050 pin surface after the test against carbon fiber, water lubricated.

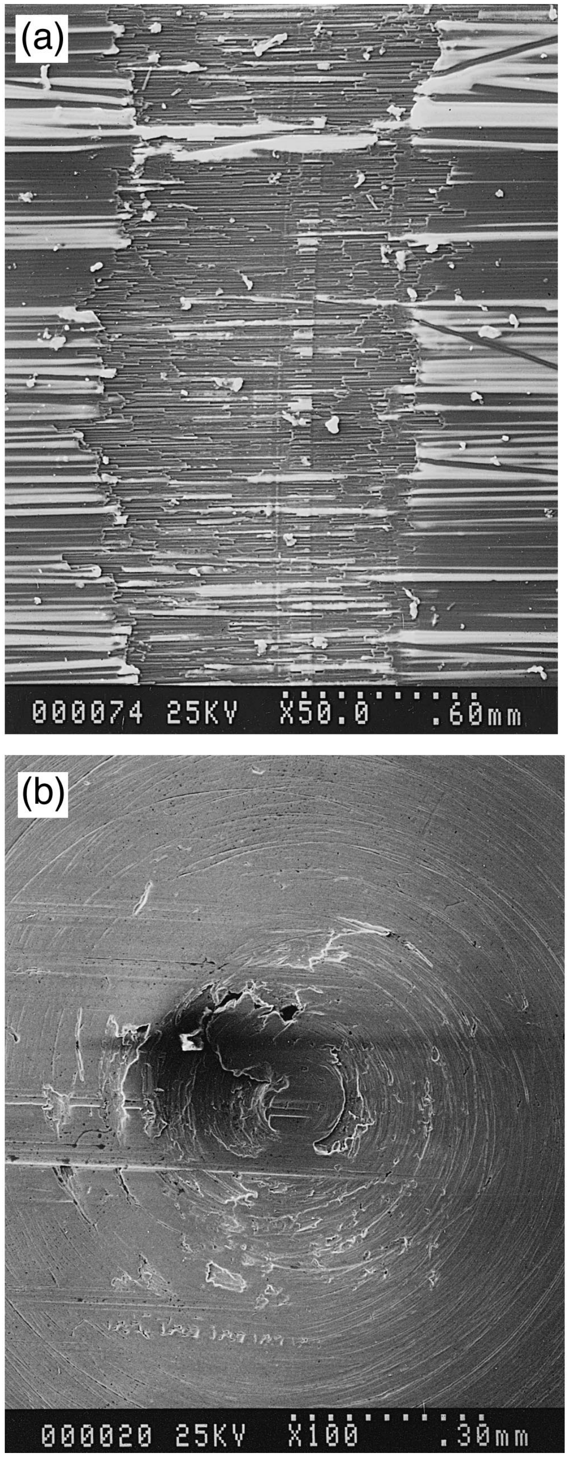

Fig. 15. a. Carbon fiber disc surface after the test against AISI 1050 pin, oil lubricated. b. AISI 1050 pin surface after the test against carbon fiber disc, oil lubricated.

the disc is much thinner with water than that obtained with oil.

Furthermore the lower viscosity of water than oil explains the lower friction factor for these couplings with water than oil [9].

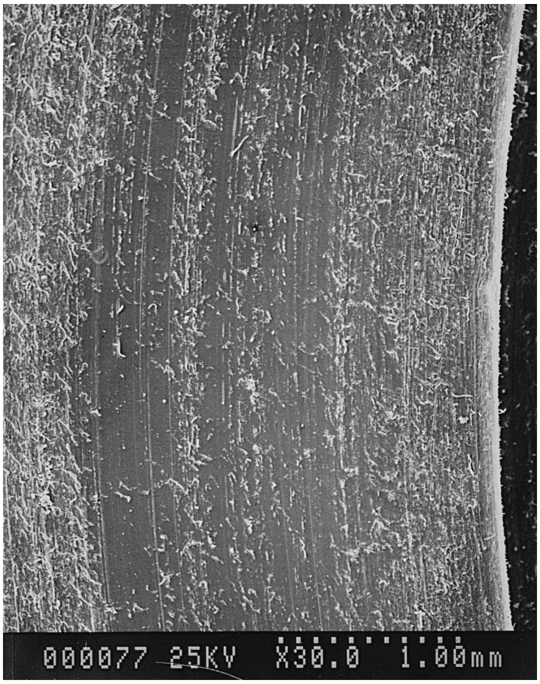

Fig. 16. PTFE disc track after test against AISI 1050 pin, water lubricated, average width 0.8 mm.

of the small surface of the pin cannot have influence on the large surface of the disc. So it is impossible to have a lifting layer of water between pin and disc.

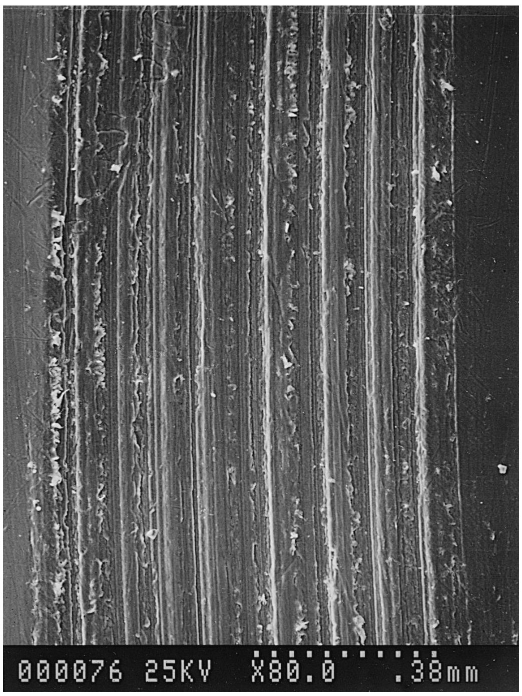

Fig. 17. PTFE disc track after test against AISI 1050 pin, oil lubricated, average width 1.5 mm.

5. Conclusions

In order to have a reduction of the friction factor and of the wear using water lubrication it is necessary that the pin–disc coupling be made of materials which have very different wettability and also that the pin has the hydrophillic characteristic.

Actually in every case with a *very hydrophobic disc* (carbon fiber and PTFE) and with a *very hydrophillic pin* (Pyrex glass and AISI 1050 steel), the usage of water lubrication has a remarkable positive effect on the system, even better than the one of the same couplings with oil.

The lubricating capability of water is due, in this kind of couplings, to the matching of two different phenomena:

- hydrostatic lifting due to the different adhesion of the molecules of water to the two different types (hydrophobic and hydrophillic) of surfaces.
- capability of water, instead of oil, to take away the wear debris.

It is very important to note that in the cases with inverted geometry, that is with a hydrophillic disc and a hydrophobic pin, the effect of surface wettability is not always evident. In effect the water adheres to the small surface of the hydrophillic pin and it is driven back from the large surface of the hydrophobic; however the opposite is not true.

6. Nomenclature

R_a (CLA) = profile mean arithmetic deviation 8DIN 4768/1, DIN 4762/1E, ISO-DIS 4287 71)
R_m maximum peak-to-valley height (DIN 4768/1, UNI 38639
R_s yield strength
R tensile stress
T normal load
N tangential load
w angular velocity

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