WATER LUBRICATION OF CERAMICS

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ABSTRACT
Present fundamental understandings on tribo-properties of ceramics in water lubrication are confirmed in the viewpoints of Stribeck curve, load carrying capacity, seizure, roughness effect, running-in and wear. Silicon carbide and silicon nitride show practically useful properties of low friction, large load carrying capacity and high anti-seizure ability in self-mated contact. These favorable properties are observed as the result of tribochemical wear and resultant smooth wear surfaces covered with tribo-films. Alumina and zirconia show relatively small load carrying capacity and poor anti-seizure ability with high friction in self-mated contact. But equivalent or better tribo-properties can be expected with the material combination of ceramic against metal. By considering these results, ceramics and water lubrication is a promising combination for the future tribo-elements.

Keywords: Ceramics, Water, Lubrication, Tribochemical Wear

1 INTRODUCTION
Modern fine ceramics including coatings are being used in a wide spectrum of practical applications under severe conditions as better materials than metals for better tribological performances. Silicon nitride, silicon carbide, alumina and zirconia are representative ceramics. Carbon-graphites, cermets such as tungsten carbides, hard coatings such as amorphous carbon and diamond-like carbon may be included in the term “ceramic” to cover all non-polymeric and non-metallic materials for tribo-elements.

Water lubrication is considered as one of the severe conditions for triboelements in comparison with oil lubrication. Because of the low viscosity of water, which is about 100 ~ 1000 times lower than those of various oil, the film thickness of water becomes much thinner than that of oil under the same hydrodynamic condition. It means that ceramic bearing must be much more sensitive than metal bearing to the surface roughness and microscopic deformation of asperities and substrate in the contact region.

Such sensitiveness of thin water film in lubrication is well modified by high elastic modulus, high hardness and tribochemical wear of ceramics in water. T. E. Fischer and H. Tomizawa clearly showed the tribochemical wear of silicon nitride in water which generated smooth enough wear surfaces (roughness below 10 nm) and introduced hydrodynamic lubrication at low speed (0.2 cm/s) and friction coefficient below 0.002 [1, 2]. The estimated water film thickness was 70 nm. Tribochemical wear of silicon carbide and generation of very smooth wear surface for hydrodynamic lubrication with water are similarly observed [4].

Lubricious film is formed on the surface of silicon nitride or silicon carbide which is thought as silicagel. It sticks on the surface strongly and works in air for a long time even after water is removed from the surface by air blow [5].

High hardness and high elastic modulus of silicon nitride help the stability of such a thin film at the contact interface between smooth wear surfaces of nanometer scale roughness.

Successful applications of ceramics to water lubricated triboelements are increasing in number. Silicon nitride ball bearing is used for the rotary shaft of a seawater pump together with tungsten carbide for the piston and cylinder [4,5]. Silicon carbide journal bearing and thrust bearing are used for water pump [7]. Silicon carbide bush against tungsten carbide is used for vertical water pump [8]. Alumina against DLC coated alumina is used for faucet valve [9]. Silicon carbide is used for water seal [10]. The cost of silicon nitride ball bearing has been reduced by a factor of ten in the past fifteen years. In this way, the cost of ceramic material would not be a major reason for avoiding ceramic application in the future.

Environmental demands at present and in the future are looking for technology of no pollution and savings of resources and energy. Water lubricated ceramic triboelements are ideal for the demands. This paper confirms the high potential of such tribo-elements with the present fundamental understandings on tribo-properties of ceramics lubricated with water.

2 STRIBECK CURVES
Fig. 1 (a) and (b) show Stribeck curves observed with ceramic/ceramic pair in water and with metal/metal pair in oil [10, 11]. Fig. 1 (a) is described with duty parameter G, and Fig. 1 (b) with lubrication number Lb, which includes the roughness effect. The friction coefficients of SiC/SiC in water at elasto-hydrodynamic and hydrodynamic lubrication regimes are much smaller than those of metal/metal pairs in oil, which is understood by viscosity effect described in hydrodynamic theory. The exact understanding of water viscosity under various contact conditions becomes very important for theoretical predictions. Other important point for practice is to know the critical conditions for the transitions of lubrication mode from elasto-hydrodynamic lubrication (EHL) to mixed lubrication (ML), from ML to boundary lubrication (BL), and finally from BL to gross seizure (GS).
3 LOAD CARRYING CAPACITY MAP

Fig. 2: Critical load for the transition from EHL to ML [13]

Fig. 2 shows the quick transition from EHL to ML at a certain critical load $W_c$ [13]. Such a critical load can be increased by introducing surface texture on a sliding surface, and the texture effect would change quantitatively depending on the contact materials and lubricants.

Fig. 3 shows the effect of pit area ratio $r$ on the normalized critical load $W_c/W_{c0}$ for SiC/SiC in water, where optimum pit area ratio for the largest critical load is obtained at around $r \approx 7\%$ [13].

Fig. 3: The effect of surface pit area ratio on the critical load $W_c$ for the transition from EHL to ML. $W_{c0}$ is the critical load on the surface of no pit [13].

Possibilities are remained to find out better surface texture than those used for Fig. 4.

4 SEIZURE MAP

When friction coefficient exceeds well over the value of 0.1 in boundary lubrication, the lubrication condition may be described as “seizure”.

Fig. 5 shows the effect of mean contact pressure and sliding velocity on friction coefficient at SiC/SiC, where the transition from hydrodynamic lubrication regime ($\mu < 0.03$) to seizure ($\mu > 0.10$) through boundary lubrication regime is clearly observed [14]. Fig. 6 shows the boundaries between the hydrodynamic regime and seizure regime including boundary lubrication regime for SiC/SiC, Si$_3$N$_4$/Si$_3$N$_4$, Al$_2$O$_3$/Al$_2$O$_3$ and ZrO$_2$/ZrO$_2$ in water with a rotary cylinder and stationary disk [14].
Theoretical hydrodynamic regimes in Fig. 6 is shown for $\eta N/P_m > 2 \times 10^{-8}$, where $N$ is rotational speed [15].

It is obvious in Fig. 6 that the friction coefficient below 0.03 is obtainable in water with SiC/SiC, Si$_3$N$_4$/Si$_3$N$_4$, Al$_2$O$_3$/Al$_2$O$_3$ or ZrO$_2$/ZrO$_2$ by choosing good combination of contact pressure and velocity. The practically important differences in these four kinds of ceramics exist in the size of regime for hydrodynamic lubrication determined by the mean contact pressure and sliding velocity; SiC/SiC pair gives the largest regime and ZrO$_2$/ZrO$_2$ the smallest on “Seizure Map”.

### 5 ROUGHNESS EFFECT ON LUBRICATED FRICTION

As shown in Fig. 7 for the repeated sliding contact of SiC/SiC in water, initial surface roughness decreases by wear and smoother surface is generated, which leads friction coefficient from initial high value such as 0.10 to lower value such as 0.03 where hydrodynamic lubrication is performed. In the regime of hydrodynamic lubrication of water, the roughness effect on Stribeck curve is clear in Fig. 8 [16]. Therefore the smoothing mechanism at contact surfaces of ceramics in water becomes next major concern.
6  RUNNING-IN PROCESS

Initial repeated sliding contact at ceramic/ceramic in water generates wear at asperity tips and low friction coefficient is attained in steady state after a certain amount of friction cycles. This process of running-in has more important role in water lubricated ceramics than in oil lubricated metals since the thickness of water film between ceramics is much thinner than that of oil film between metals.

Fig. 9 shows that friction of Si₃N₄/Si₃N₄ drops more quickly than that of SiC/SiC and the steady state value of friction coefficient is 0.01 for SiC/SiC and 0.005 for Si₃N₄/Si₃N₄ although both of them have the similar initial roughness of about 0.20 μm [4]. Careful analysis of wear scar on SiC shows that mechanical wear is predominant until about 7×10⁴ cycles and then tribochemical wear dominates to generate smooth wear surface for hydrodynamic lubrication.

Fig. 10 shows the critical friction cycle for running-in as shown in Fig. 10, where SiC/SiC takes much more cycles than Si₃N₄/Si₃N₄ as the initial surface roughness increases [4].

After having smooth enough wear surface by running-in with good conforming, lubrication property of water film becomes the next concern. Fig. 11 shows the velocity dependency of friction coefficients of SiC/SiC and Si₃N₄/Si₃N₄ observed after running-in in water. In the case of SiC/SiC, friction coefficient does not show the hysteresis in the process of velocity change. But in the case of Si₃N₄/Si₃N₄, friction coefficient suddenly rises to a very high value at a certain velocity in the decreasing process of velocity, and it decreases slowly in the process of velocity increase. Such a difference in friction behavior would depend on the wear property of tribo-film formed on the wear surface, and so the understandings on wear mechanisms become important for water lubrication.

7  WEAR MECHANISMS IN WATER

7.1  Mechanical and tribochemical wear in sliding

Fig. 12 shows the wear mode transition of Si₃N₄ from mechanical wear to tribochemical wear in the running-in process [17]. Mechanical wear takes place at the early stage of running when initial surface asperities are in contact with high contact stresses. Crystalline wear particles are formed by transgranular or intergranular fracture, and pits are generated on wear surface. As the contact surfaces have better conforming by wear, tribochemical film grows on wear surface and it is removed from the surface by forming fine rolls or dissolved into water. This tribochemical wear is thought to have the following chemical reactions [2, 3].

\[
\begin{align*}
\text{Si}_3\text{N}_4 + 6\text{H}_2\text{O} & \rightarrow 3\text{SiO}_2 + 4\text{NH}_3 \\
\text{SiO}_2 + 2\text{H}_2\text{O} & \rightarrow \text{Si(OH)}_4
\end{align*}
\]

Generation of NH₃ is experimentally confirmed, and the volume of NH₃ is proportional to the wear volume [18].
Fig. 12: Wear mode transitions of Si$_3$N$_4$ during running-in of Si$_3$N$_4$/Si$_3$N$_4$ sliding in water at initial roughness $R_{\text{rms}} = 0.058$ µm on disk surface [17].

Fig. 13 shows typical wear surface profiles of pin and disk made of Si$_3$N$_4$, where very smooth wear surfaces and good conforming of two surfaces are observed. It is the result of tribochemical wear which enables hydrodynamic lubrication of water [17].

Wear process of running-in is described as a function of sliding distance in Fig. 14 for SiC/SiC and Si$_3$N$_4$/Si$_3$N$_4$. Wear rates are calculated from the curves in Fig. 13 and shown in Table 1 [4].

The wear rate in the initial wear is mainly determined by mechanical wear, but chemical wear is partly joined. The wear rate in the steady wear is mainly determined by tribochemical wear. If sliding would be continued further, smaller wear rate in the ranges of $10^{-9}$ mm$^3$/Nm and $10^{-10}$ mm$^3$/Nm would be generated [19].

Remaining task is to introduce wear models and wear equations. Some challenges have been already made for mechanical wear and tribochemical wear although they are not yet ready for practical design [20, 21, 22, 23].

7.2 Mechanical and tribochemical wear in rolling-sliding

Tribochemical wear dominates in pure rolling contact even when rolling of Si$_3$N$_4$/Si$_3$N$_4$ is made in humid air at high contact pressure above 1.0 GPa and extremely smooth wear surfaces are generated [24, 25]. Introduction of slippage in rolling contact increases the possibility of mechanical wear with crack propagation driven by additional shear stress at the contact interface.

Fig. 14: Wear curves of SiC pin and Si$_3$N$_4$ pin sliding against a disk of the same material in water. These wear curves correspond to the friction curves in Fig. 9 [4].

<table>
<thead>
<tr>
<th>Wear rate of SiC pin against SiC disk in water (mm$^3$/Nm)</th>
<th>Initial wear</th>
<th>Steady wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear rate of Si$_3$N$_4$ pin against Si$_3$N$_4$ disk in water (mm$^3$/Nm)</td>
<td>$2.8 \times 10^{-6}$</td>
<td>$2.1 \times 10^{-7}$</td>
</tr>
<tr>
<td>$4.0 \times 10^{-6}$</td>
<td>$5.7 \times 10^{-8}$</td>
<td></td>
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</tbody>
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Table 1: Wear rate in running-in
The broken line in Fig. 15 shows the boundary between tribocatalytic wear regime and mechanical wear regime observed in air of 55% RH [26]. The solid line in the figure shows the boundary of the same meaning observed in air with water lubrication. It is obvious from Fig. 15 that water lubrication extremely expands the regime of tribocatalytic wear on the wear mode map.

8 MATERIALS COMBINATION

8.1 Self-mated ceramics in water

SiC/SiC and Si₃N₄/Si₃N₄ are already practically established combinations for water lubricated ceramic tribo-elements in the past fifteen years. Load carrying capacity of SiC or Si₃N₄ is much larger than that of Al₂O₃ or ZrO₂ [26]. For further applications and improvements of tribological performances under severe working conditions, there is much to do in fundamental research.

Al₂O₃/Al₂O₃ is other attractive combination for water lubrication. A lubricious trihydroxide (Al(OH)₃) layer is formed on a wear surface and it reduces wear and friction in water [28, 29]. Sliding wear rate and friction coefficient start with 2.4×10⁻⁹ mm³/Nm and µ ≏ 0.2 in the initial state and they increase to 1.6×10⁻⁸ mm³/Nm and µ ≏ 0.3 in the steady state [30].

These wear rate values are low enough to have water lubrication of Al₂O₃/Al₂O₃ for practice. It is already shown in Fig. 6 that Al₂O₃/Al₂O₃ has hydrodynamic regime under a certain combination of contact pressure and sliding velocity in water.

It is important to notice that Al₂O₃/Al₂O₃ (Ra ≏ 0.03 µm) shows smaller wear rate of 3.4×10⁻⁹ mm³/Nm in air than in water (3.4×10⁻⁹ mm³/Nm) under the contact pressure of 1.0 MPa [31]. Even increase of room humidity increases wear of Al₂O₃ [32].

ZrO₂/ZrO₂ shows similar wear behavior to Al₂O₃/Al₂O₃. Wear rate of tetragonal zirconia, which has high fracture toughness of 11.6 MPa·m¹/₂, is in the order of 10⁻⁸ mm³/Nm at the initial wear in air, but it increases to the order of 10⁻⁷ mm³/Nm in water. Intergranular fracture, which may be induced by water brittleness, is observed as a major wear mechanism for such a high wear rate [33]. In comparative rolling-sliding tests of tough ZrO₂ (13.9 MPa·m¹/₂) and Si₃N₄ (4.1 MPa·m¹/₂) in water with 10% slip and 3 MPa contact pressure, ZrO₂/ZrO₂ shows the wear rate in the order of 10⁻⁷ mm³/Nm with friction coefficient of 0.4 and Si₃N₄ shows 10⁻⁸ mm³/Nm and 0.05 respectively [34].

Because of such tribo-properties of ZrO₂/ZrO₂, its application in water is rather limited.

8.2 Ceramic against metal in water

Hydrodynamic lubrication observed with Si₃N₄/Si₃N₄ after running-in in Fig. 8 is similarly observed with Si₃N₄/Cast Iron [35]. Friction coefficient is 0.7 at the starting point and it is reduced to below 0.02 after 2000 m sliding.

A tribo-film which consists of silica gel, graphite, Fe₂O₃, and crystal SiO₂ is formed on the wear surface of cast iron [36]. This suggests that Si₃N₄/metal may have a chance to give equivalent or better tribological performance than of Si₃N₄/Si₃N₄ in water depending on practical needs as shown in [5] where WC/ Si₃N₄ is shown as a good combination for lake water pump.

In the case of alumina, the combination of Al₂O₃/Steel shows much better performance in Stribeck curve than Al₂O₃/Al₂O₃ in water as shown in Fig. 16 [37]. These results above introduced strongly suggest that some ceramic/metal combinations may give better tribological performances in water than ceramic/ceramic combinations.

9 CONCLUSION

Present understanding on fundamental friction and wear properties of ceramics in water are introduced, and the practical usefulness of water lubrication of ceramics is confirmed in the viewpoints of friction coefficient, load carrying capacity, seizure load and wear.

If we would remember that the pioneering study on ceramic ball bearing was made in 1961 [38] and an incubation period for fundamental researches [39, 40, 41] were necessary until 1985 when commercial ceramic ball bearing appeared in the market, we may expect a big progress in the technology of water lubrication of ceramics in the coming twenty years as the environmental demands become stronger.

10 ACKNOWLEDGMENT

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11 REFERENCES


Fig. 16: Stribeck curves for alumina sliding in water against three different materials; Al₂O₃, steel, graphite [37].


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