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The critical condition for the transition from HL to ML in water-lubricated SiC

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Silicon carbide (SiC) with water lubrication is being considered as the most promising combination to replace metals and oil for sliding bearings and mechanical seals of machines working in water. The basic properties of the Stribeck curves of water lubricated SiC in parallel contact, especially, the critical conditions for the transition from HL to ML were studied experimentally. The hydrodynamic lubrication regions and minimum friction coefficients of metal pair in oil and SiC pair in water are compared to give a quantitative value of the oil viscosity range, in which metal/oil can be directly replaced by SiC/water for triboelements.

In order to improve the load-carrying capacity of SiC sliding bearings for the increasing strict demands from industry, a surface texture was introduced to one of the contact surfaces by means of reactive-ion etching. The effect of surface texture on the lubrication regimes and the minimum friction coefficient were evaluated experimentally.

KEY WORDS: Stribeck curve; SiC; water lubrication; surface texture

1. Introduction

Saving energy and reducing the amount of pollution released to the environment have increasingly become the most important trends in machine design. Instead of metal and oil, silicon carbide is considered as a promising material for sliding bearings and mechanical seals working in water due to its excellent tribological properties such as anti-wear, anti-seizure, anti-corrosion, and in particular, very low friction while it slides against the same material in water. This development has simplified machines working in water and made maintenance easier, since the process fluid is used as a lubricant so that a special oil lubricating system is not necessary [1–5].

In the past, water lubrication was considered as a severe condition for triboelements in comparison to oil lubrication. Besides the corrosion problem, the viscosity of water is only $1/10 \sim 1/100$ that of oil usually used, and therefore, the lubricating film of water is much thinner than that of an oil film generated under the same hydrodynamic conditions.

In 1987, Tomizawa and Fischer found that silicon nitride under water lubrication exhibits low friction and revealed that the key of this phenomenon is tribo-chemical reaction [6]. The contact surfaces become very smooth due to tribo-chemical wear, and the reaction product SiO_2 dissolves in water as silicic acid, which is presumed to act as a lubricant [7]. Low friction of SiC under water lubrication could also be explained by the same mechanism [8–9].

Because the friction coefficient in these cases is extremely low and it depends on the relative sliding speed, the word "hydrodynamic" has been used to describe the low friction of Si-based ceramics under water lubrication since then [6–9].

However, is the "hydrodynamic lubrication" of Si based ceramics sliding in water the same as that of metals in oil? There has been little work concerning the behavior of this kind of hydrodynamic lubrication.

On the other hand, so far, the mechanism of the load-carrying capacity generated between parallel sliding surfaces is still a difficult problem since many variables, such as surface roughness, waviness, thermal or viscosity wedge, squeeze films, etc., are contributing factors. Thus, it is rarely possible to calculate or predict the performance of parallel sliding surfaces accurately [10–11]. Compared to journal bearings, there are only few well-documented studies on the Stribeck curves of thrust bearings [11–14]. In 1987, Lebeck, based an experimental data, showed that in the case of metals lubricated by oil, the transition from a mixed to a hydrodynamic lubrication regime occurs at the value of duty parameter $G\,(=\eta VB/W)$ around 10^{-6} [11].

Therefore, the purpose of this research is to study the properties of the hydrodynamic lubrication of thrust-slid SiC in water, to evaluate its ability to establish hydrodynamic lubrication by comparing its Stribeck curves to those of metals under oil lubrication, and furthermore, to study the effect of surface texture on the hydrodynamic region of SiC under water lubrication.

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Table 1
Properties of the oil.

	Viscosity (mm^2/s)		Viscosity index	Density (g/cm^3)	Total acid number (mgKOH/g)
	40 °C	100 °C			
P60	7.79	2.21	83	0.856	0.01
P60 + 0.5% S.A.	7.79	2.21	83	0.856	1

2. Experiment

2.1. Specimens

The specimens were made of stainless steel, bronze and silicon carbide (sintered without pressurization). Purified water, paraffin oil P60 and P60 with oiliness additive, i.e., 0.5% stearic acid, were used as lubricants. The properties of the oil are listed in table 1.

Sliding tests were performed between the flat surfaces of a cylinder and a disk by rotating the cylinder. Figure 1 shows a pair of specimens made of SiC. The upper specimen is in the shape of a cylinder, which has a hole in center and two grooves (4 × 0.5 mm) on the flat surface so as to supply lubricant to this surface. The Lower specimen is in the shape of a disk. The metal specimens have the same shape as that of the SiC shown in figure 1.

The combinations of the specimens and lubricant are listed in table 2.

In order to increase the load-carrying capacity of SiC in water, the flat surface of the disk was textured with micro-pits arranged in a square array as shown in figure 2.

Reactive ion etching (RIE) was used to produce micro-pits on the flat surface of the disk. RIE is a widely used method for the processing of MEMS and ICs. It ionizes a reactive gas by electric discharge, then accelerates these ions to sputter and react with the target. Since the material is mainly removed in the direction of ion movement, the pit was formed in the shape of a round crater, as shown in figure 2. The round wall of the pit is near normal to the flat surface. The diameter and arrangement of the pits were determined by a metal mask on the surface. The depth of pits was controlled by the etching time.

Experiments were carried out with disks that have pits with diameters ranging from 50 to 650 μm, depths from 2.0 to 16.6 μm, and pit-area ratios from 0 to 22.5% [15].

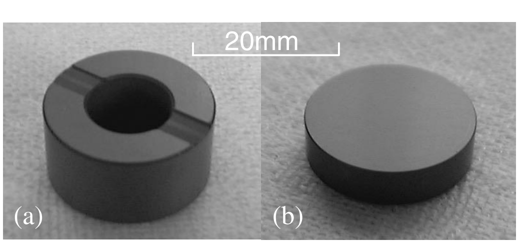

Figure 1. Photographs of the specimens made of SiC (a) Cylinder (b) Disk.

Table 2
Specimens and lubricants.

	Lubricant	Cylinder	Disk
1	Purified water	SiC	SiC
2	P60 (oil)	Bronze	Stainless steel
3	P60 + 0.5%S.A.	Bronze	Stainless steel
4	Purified water	SiC	Textured SiC

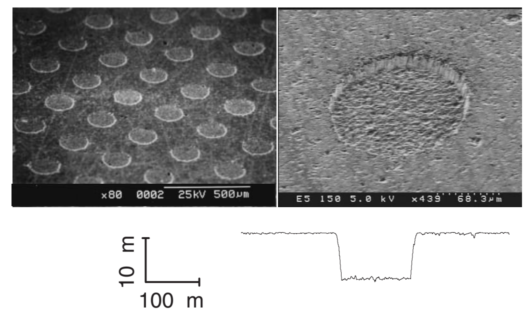

Figure 2. The SEM photographs and cross profile of the micro-pit produced by RIE.

However, in this paper only the best result, which was observed from the pit pattern of 350 μm in diameter, 3–4 μm in depth and 5% in pit area ratio, is shown for comparison with untextured SiC and metals in oil.

2.2. Apparatus

Figure 3 shows the apparatus used in this experiment. The cylinder is in contact with the disk and is driven by a motor with an adjustable rotational speed. The disk is supported by a half-spherical pivot so that its friction surface is automatically aligned to match the surface of the cylinder. The Load is applied by a hydraulic system from the bottom of the disk. Purified water is filled into the center hole of the cylinder at a supply rate of 60 ml/min. The temperature of the water before and after friction is monitored by thermocouples. Load and friction torque are detected by load cells. An air

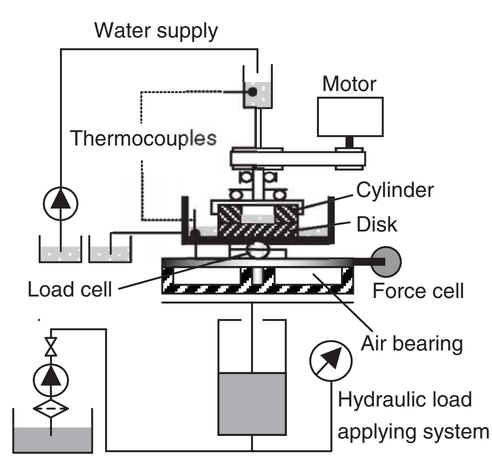

Figure 3. Schematic diagrams of apparatus.

bearing is used to support the disk so that very small friction torque (< 0.001 Nm) can be accurately detected.

An auto-stop system is used to stop the load applying system and the driving motor to avoid damage to the apparatus and specimens when the friction torque increases rapidly.

The temperature of the lubricants supplied to the friction surfaces was controlled at around 20 °C as past studies have shown that temperature has a large effect on the friction of ceramics.

2.3. Results

After a simple running-in process, the friction force of the material combinations listed in table 2 was measured with increasing load at the given rotational speeds of 200, 400, 600, 800, 1000, and 1200 rpm. Then the friction coefficients were calculated for each case.

Figure 4 is an example result of the relationship between friction coefficient and load obtained at a rotational speed of 800 rpm. The common feature of these four curves is that they have low friction regions while load is light, and after the load exceeds a certain value Wc, the friction coefficient increases rapidly.

Since the parameter Wc is a measure of "critical load at low friction", it can be used as an index to evaluate the load-carrying capacity of each material combination. It is obvious that even with water lubrication, the Wc of SiC is greater than that of a metal lubricated by oil. Moreover, with proper surface texture, the Wc of SiC is increased to a value that is about 2.5 times higher than before.

For the case of metals lubricated by oil, the oiliness agent, stearic acid added to the oil did not show an obvious effect on the critical load Wc under the experimental conditions used. But with this additive, the increasing rate of friction after Wc was slowed down. Since the region of increasing friction (W > Wc) is actually a mixed and boundary lubrication regime, it is reasonable that oiliness agent is effective to reduce friction in this region where some contact occurs.

In the low-friction region (W < Wc) of each case, the friction coefficient of SiC/water is lower than that of metal/oil. Possibly, the different surface roughness is a contributive factor. But with a proper load, the contact surfaces of SiC become smooth due to tribo-chemical wear while sliding in water, meanwhile, some wear scars are easily generated on the surface of metal even as the friction coefficient is decreasing. So the difference between SiC/water and metal/oil is that the SiC pair in water is capable of generating smooth surfaces to obtain low friction by themselves.

In order to investigate the behavior of the "hydrodynamic lubrication" of water-lubricated SiC, Stribeck curves are drawn and compared to those of metals lubricated with oil.

The duty parameter $G = \eta N/Pm$ was used in these figures, where η [Pa · s] is the dynamic viscosity of the lubricant, N [s^{-1}] is the rotational speed and Pm [Pa] is the effective mean contact pressure.

The viscosity of water at 20 °C is 0.001 [Pa · s]. The viscosity of oil P60 at 20 °C is 0.0132 [Pa · s], which is calculated from its kinematic viscosity at 40 °C and 100 °C by Walther's equation [16] as below:

$$\log\log(\nu + 0.7) = A - B\log T$$
$$\eta = \nu \cdot \rho$$

where ν is the kinematic viscosity of oil used, i.e., $\nu = 7.79\,mm^2/s$ at 40 °C and $\nu = 2.21\,mm^2/s$ at 100 °C. A and B constants are determined for each lubricant, T is the absolute temperature and ρ is the density of lubricant.

Figure 5 shows the Stribeck curves of SiC lubricated with water. There are six curves obtained at the rotational speeds of 200, 400 ... 1200 rpm respectively. Every curve in this figure exhibits a clear transition of friction from a low and stable region to an increasing region. For each curve, the part of low and stable friction has been termed the regime of hydrodynamic or thick-film lubrication, where a complete film of the lubricant supposedly separates the rubbing surfaces. The

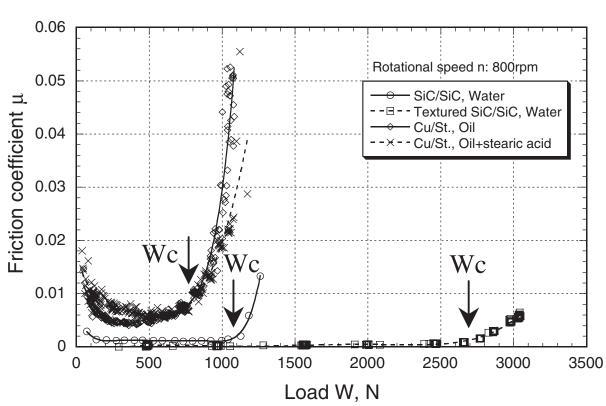

Figure 4. Friction coefficient μ versus load W at a rotational speed of 800 rpm.

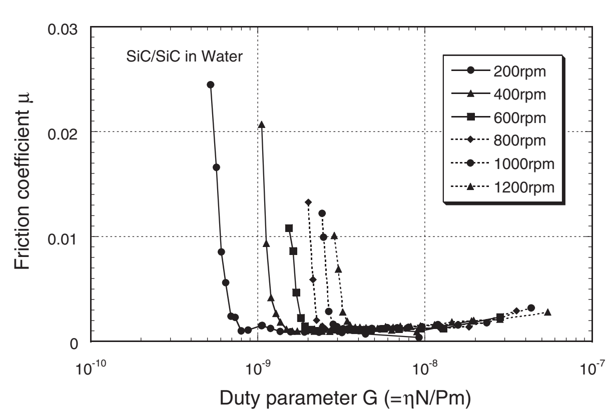

Figure 5. Stribeck curves of SiC sliding in water at the given rotational speed of 200, 400 ... 1200 rpm.

part of increasing friction has been termed the region of mixed and boundary lubrication, where contact occurs in some areas. The region between hydrodynamic lubrication and mixed lubrication, i.e., the transition region is called thin-film lubrication or elastohydrodynamic lubrication, where the oil film has become so thin that the viscosity no longer is the sole factor, and the deformation and the real viscosity of the thin film need to be taken into account.

It is obvious that the data obtained from different rotational speeds cannot be unified into one curve as supposed by the classic hydrodynamic theory. These curves shift in the X direction according to different rotational speeds.

In order to understand this phenomenon, experiments of metal/oil were carried out. Their Stribeck curves at different rotational speeds were drawn in same way.

Figure 6 shows the Stribeck curves of metal pairs lubricated with P60 oil. Except for the data observed at 200 rpm, the curves clearly exhibit a transition from hydrodynamic to mixed lubrication in the rotational speed range from 400 rpm to 1200 rpm. These Stribeck curves have almost the same value of duty parameter G, which separate hydrodynamic lubrication region and mixed lubrication region. The different rates of increase of friction coefficient in the mixed lubrication regime show the speed dependency of friction in this region.

Figure 7 shows the Stribeck curves of the metal/oil combination after the oiliness agent, 0.5% stearic acid was added to the oil. The friction at 200 rpm was still high and unstable such that the Stribeck curve does not show a clear transition from hydrodynamic to mixed lubrication. Compared to figure 5, with stearic acid, the Stribeck curve also shifts in the X direction while rotational speed was changed in the range from 400 rpm to 1200 rpm. This is similar to the behavior of SiC in water, as shown in figure 5.

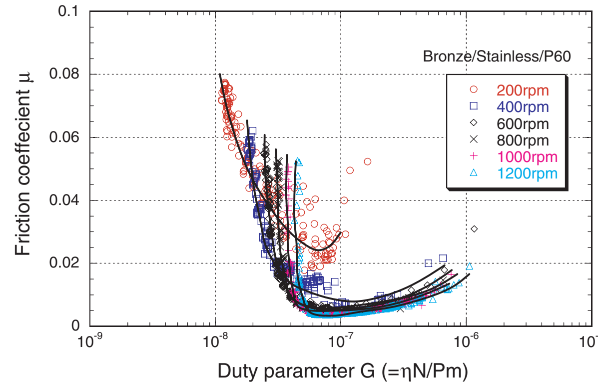

Figure 6. Stribeck curves of a Bronze/Stainless pair lubricated by P60 at the given rotational speed of 200, 400 . . . 1200 rpm

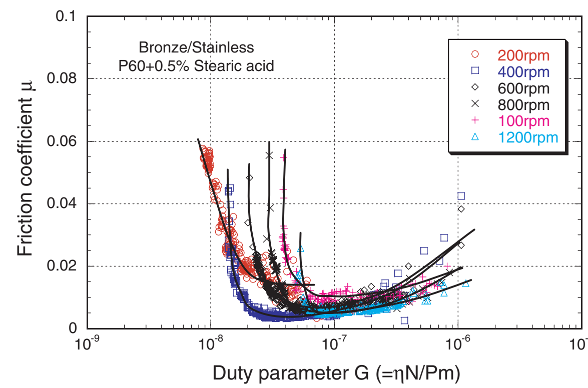

Figure 7. Stribeck curves of a Bronze/Stainless pair lubricated by P60 + 0.5% stearic acid at the given rotational speed of 200, 400 . . . 1200 rpm

It also found that the Stribeck curve of SiC/water shifts in X direction according to rotational speed. The reason, according to current understanding, is that the tribochemical products form a film on the friction surface. It is effective in reducing friction while two surfaces begin to contact, especially in the low-sliding-speed range.

3. Discussion

3.1. *Speed effect on Stribeck curve*

Both in the case of SiC/water and metal/oil (P60 + 0.5% stearic acid), the Stribeck curve shifts in the X direction according to the change of rotational speed.

For metal/oil (P60 + 0.5% stearic acid), it can be explained as the effect of oiliness agent. Oiliness agents are helpful to generate a thin adsorbed film on the surface to reduce friction while surface contact happens. Generally, this film is destroyed under high-speed conditions but reforms during slow running [17]. It means this agent is effective in the low speed range rather than in the high speed range. Therefore, the Stribeck curve obtained at low speed shifts to the left side of that obtained at high speed as shown in figure 7.

3.2. *Load-carrying capacity*

As shown in figure 4, the critical load Wc of SiC/water is greater than that of metal/oil. This means the combination of SiC/water has higher load-carrying capacity, and can be used for triboelements instead of metal/oil directly under same dynamic conditions. However, the viscosity of the oil used here is really very low and high viscosity results in a thick fluid film, which means high load-carrying capacity. This raises the question: in what viscosity range, metal/oil can be replaced by SiC and water lubrication directly?

In order to answer this question, the Stribeck curves obtained in this experiment were compiled in one figure for comparison. Additionally, some well-documented experimental results of the sliding of parallel surfaces

Table 3
Experimental conditions of related researches.

Source	Lubricant η, Pa·s	Configuration	Materials	Roughness μm
Lenning, 1960	Oil 17–67 × 10^{-3}	Six rectangular pads/disk	Cast Iron/52100 steel	0.05/0.13
Brix, 1962	Oil 70 × 10^{-3}	Four 13 mm dia. pads/disk	Phosphor bronze/Ni–Cr steel	?/0.15
Kanas, 1984	Water 0.7 × 10^{-3}	Three circular pads/disk	Carbon/tungsten-carbide	0.2/0.05

were also drawn in the same figure to help our understanding of the hydrodynamic region of metal/oil and SiC/water.

Table 3 shows the experimental conditions of some well-documented test results by Lenning [13], Brix [12], and Kanas [11]. Figure 8 shows the Stribeck curves compiled from these references and those obtained in this research. For the authors' results, the Stribeck curve shifts in X direction according to rotational speed. Therefore, only the data at 1200 rpm are used in this figure.

Brix's result presents a typical trend of Stribeck curve for metal/oil. Lenning's result seems to be an extension line of the Brix's curve. Otherwise, if the shape near the right end of Lenning's curve is the transition region from hydrodynamic to mixed, the G value of the transition is close to the results of our experiment of metal/oil, although the sliding pair and lubricant are different.

It is clear that it is easier to establish hydrodynamic lubrication for SiC/water than for metal/oil. The transition point of metal lubricated with oil is in the range of G between 10^{-8} and 10^{-6}. The smallest G value of transition points of metal/oil obtained from our experiment, is 6.7×10^{-8}. Comparatively, the Stribeck curve of SiC/water is on the left of the metal/oil values. The G value of SiC/water at the transition position is 4.8×10^{-9}, approximately 1/15 that of metal/oil.

Under the same load and sliding speed, lower G value of the transition means that hydrodynamic lubrication can be established with lower viscosity. By comparing the G value at the transition point of SiC/water and metal/oil, it is understandable that when the viscosity of oil is 15 times that of water, SiC/water and metal/oil establish the hydrodynamic lubrication at the same dynamic conditions (N/Pm). Therefore, when the viscosity of oil is lower than 15 times that of water, the performance of the triboelements would not be impaired if metal/oil was replaced by SiC/water.

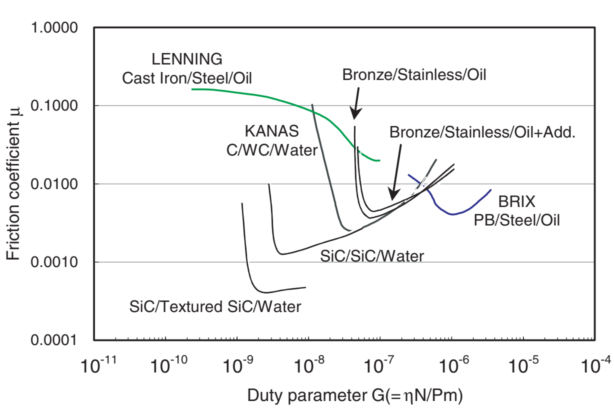

Figure 8 Stribeck curves as a function of duty parameter $G = \eta N/Pm$.

Furthermore, with a proper textured sliding surface, the Stribeck curve of SiC has a left shift again. The G value of the transition point is about 1.9×10^{-9}, means, it has decreased to the value 2/5 that of untextured SiC in water lubrication.

It also can be found that in the hydrodynamic lubrication regime, friction coefficients of C/WC and SiC/SiC in water are lower than that of metal in oil, and the textured SiC with water lubrication has the lowest friction coefficient.

Although duty parameter G describes the severity of the operating conditions, its disadvantage is that it does not include any surface parameters. As a consequence, another parameter, i.e., the lubrication number L_b was suggested and defined as [18]:

$$L_b = \frac{\eta V}{R_{at} Pm}$$

where η is the dynamic viscosity in Pa·s, V is the sliding velocity in m/s, Pm is the normal pressure in N/m^2 on sliding surface and R_{at} is the combined surface roughness given by:

$$R_{at} = \sqrt{R_{a1}^2 + R_{a2}^2}$$

where R_{a1} and R_{a2} are the average roughness of mating surfaces respectively.

Figure 9 shows the Stribeck curves using the lubrication number L_b as the X coordinate. In this figure, the hydrodynamic regions of nonmetal/water combinations are still larger than those of metal/oil. Compared with figure 8, the Stribeck curve of C/WC/water moved to the left side of SiC/water. The expression of L_b indicates that in order to establish hydrodynamic lubrication, a smooth surface is necessary. Fortunately, under proper operational conditions, a smooth sliding surface of SiC can be generated gradually due to tribo-chemical wear. This means SiC/water is capable of improving their contact conditions, thus establishing hydrodynamic lubrication by themselves.

With a proper textured surface, the L_b value of SiC, at which lubrication transitions from mixed to hydro-

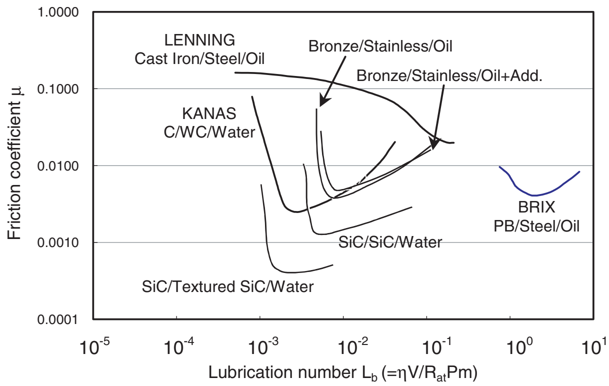

Figure 9. Stribeck curves as a function of lubrication number $L_b = \eta V/R_{at}Pm$.

dynamic regime, is a little bit lower than that of C/WC/water.

4. Conclusions

In order to investigate the behavior of the "hydrodynamic lubrication" of water lubricated SiC in parallel contact, experiments were carried out. The results were compared to those of metals lubricated with oil and the experimental data found in the literature. The following conclusions have been drawn as the most significant:

(1) The Stribeck curve of SiC lubricated with water presents a clear transition of lubrication mode from hydrodynamic to mixed. The duty parameter G, at which transition occurs, is affected by rotational speed.
(2) The ability to generate hydrodynamic lubrication of SiC in water is significantly higher than that of metal in oil. Experimental results show that SiC/water can be used for triboelements instead of metal/oil below the viscosity 15 times that of water.
(3) Furthermore, proper texture of sliding surface can expand the hydrodynamic region of SiC under water lubrication. In this experiment, it decreases the transition G value to about 2/5 of that of an untextured pair.

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References

[1] S. Asanabe, Tribol. Int. 20 (1987) 355.
[2] Y. Kimura, J. Turbo-Machinery 24 (1996) 41.
[3] S. Ishibashi, K. Yamashita, H. Kono and T. Komura, J. Turbo-Machinery 15 (1986) 163.
[4] P. Andersson and P. Lintula, Tribol. Int. 27 (1994) 315.
[5] B.S. Nau, J. Mech. Eng. Sci., IMechE 204 (1990) 349.
[6] H. Tomizawa and T.E. Fischer, ASLE Trans. 30 (1987) 41.
[7] S. Sasaki, J. Jap. Soc. Lubr. Eng. 33 (1988) 620.
[8] H.C. Wong, N. Umehara and K. Kato, Wear 218 (1998) 237.
[9] M. Chen, K. Kato and K. Adachi, Tribol. Inte. 35 (2002) 129.
[10] L.P. Ludwig and H.F. Greiner, Mech. Eng. 100 (1978) 18.
[11] A.O. Lebeck, J. Tribol. 109 (1987) 189.
[12] V.H. Brix, Lubri. Eng., (1962) 7, 312.
[13] R.L. Lenning, Lubri. Eng. (1960) 12, 575.
[14] A. Vezjak and J. Vizintin, J. STLE, Lub. Eng. (2001) 1, 17.
[15] X. Wang, K. Kato and K. Adachi, Tribol. Trans. 45 (2002).
[16] V. Stepina and V. Vesely, *Lubricants and Special Fluids*, (Elsevier, 1992).
[17] M. Ratoi, V. Anghel, C. Bovington and H. A. Spikes, Tribol. Int. 33 (2000) 241.
[18] D.J. Schipper, A.J. Hoevenaar, B. deLaat, S. Bakx and J.T. Keijer, *Proc. 13th Int'l. Conf. on Fluid Sealing*, ed. B. S. Nau, (Kluwer Academic Publishers, 1992), p. 467.