Influence of surface roughness parameters and surface morphology on friction performance of ceramics

Weizheng ZHANG1, Seiji YAMASHITA2,4, Takeshi KUMAZAWA3, Fumihito OZEKI3, Hideki HYUGA4 and Hideki KITA1

1Nagoya University, Graduate School of Engineering, Department of Chemical Systems Engineering, Nagoya 4648603, Japan
2Nagoya University, Graduate School of Engineering, Department of Materials Process Engineering, Nagoya 4648603, Japan
3Mino Ceramic Co., Ltd, Technical Research Laboratory, Handa, Aichi 4750027, Japan
4National Institute of Advanced Industrial Science and Technology, Ceramic Microstructure Control Group, Structural Materials Research Institute, Nagoya 4638560, Japan

Influence of both surface roughness and surface morphology on frictional behavior of ceramics during run-in period under dry sliding was investigated simultaneously. Similar average surface roughness ($R_a = 0.01-0.02 \mu m$) was produced for the three ceramics: monolithic boron carbide ceramics, boron carbide-silicon carbide composite ceramics and monolithic silicon carbide ceramics. Surface roughness parameters show some influence on friction processes, however, surface morphology is considered as a more important competitive factor. Lower friction coefficient during run-in period and shorter sliding distance up to the steady state condition were observed for the $B_4C-SiC$ composite ceramics, which has a different surface morphology from those of monolithic $B_4C$ ceramics and monolithic $SiC$ ceramics.

Key-words : Roughness parameters, Surface morphology, Nanorelief structure, Friction

1. Introduction

Advanced structural ceramics as tribo-elements get more and more extensive attention, such SiC ceramics, $B_4C$ ceramics, $Si_3N_4$ ceramics, $Al_2O_3$ ceramics, $ZrO_2$ ceramics and some composite ceramics.13–8) Therefore, studies on friction property between the two mating surfaces are becoming more and more widely. It is well known that two significant surface characteristics are surface roughness and surface morphology. Initial surface roughness has a significant effect on frictional behavior at the friction interface.9) Meanwhile, surface morphology also has an important influence on friction processes.10) It is widely reported that higher initial surface roughness can cause lower friction coefficient and lower initial surface roughness results in higher coefficient of friction.11) At present, most of research on the influence of surface roughness parameters on tribological properties is focused on average surface roughness ($R_a$). In fact, other surface roughness parameters also have effects on tribological properties of ceramics. On the other hand, in particular, there are some differences for the surface morphology between composite ceramics and monolithic ceramics after polishing before application. For example, nanorelief structure is found on the surface of $B_4C-SiC$ composite ceramics.12) Different surface morphologies also have different effects on frictional behavior. Average surface roughness ($R_a$) is defined as arithmetic mean of the absolute values of vertical deviation from the mean line through the profile. Although $R_a$ can describe height variations well, other information, such as the shapes, slopes, and sizes of the asperities and the regularity and frequency of their occurrence, can’t be provided. It is possible that the profiles have the same $R_a$ values, but different frequencies or different shapes. Thus, surface roughness parameter $R_a$ can’t describe contact surface sufficiently. The standard deviation ($R_q$) is the square root of the arithmetic mean of the square of the vertical deviation from the mean line, which is more sensitive to deviations from mean line than $R_a$. Average peak-to-valley height ($R_p$) is defined as the distance between average of the five highest asperities and average of the five lowest valleys. Kurtosis ($R_{ku}$) represents the probability density sharpness of the profile. For surface profile with a symmetric Gaussian distribution, $R_{ku}$ equals to 3. For surface profile with leptokurtic, $R_{ku}$ is more than 3, and $R_{ku}$ is less than 3 for surface profile with platykurtic. Skewness ($R_{sk}$) describes the degree of asymmetry of the density function and is sensitive to occasional deep valleys or high peaks. For surface profile with the Gaussian distribution, $R_{sk}$ is equal to zero. For surface profile with high peaks or filled valleys, $R_{sk}$ is positive. For surface profile with deep

† Corresponding author: S. Yamashita; E-mail: yamashita.seiji@material.nagoya-u.ac.jp

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scratches or loss of peaks, Rsk is negative. A schematic of surfaces with Rku values higher and lower than 3 and with positive and negative Rsk is shown in Fig. 1.

In practical applications, frictional behavior of ceramics is usually affected by both surface roughness and surface morphology. However, the studies focus on frictional property of ceramics by investigating both surface roughness and surface morphology simultaneously are limited. The goal of this work is to study the effects of both surface roughness and surface morphology on frictional behavior of ceramics simultaneously.

2. Experimental procedure

In order to investigate effects of surface roughness parameters and surface morphology on the frictional behavior, three different samples were used in this experiment. The composition of the three samples were monolithic B4C ceramics with sintering additives of 3 wt% SiC and 3 wt% C (hereafter referred to as B), B4C–40 wt% SiC composite ceramics with a sintering additive of 3 wt% C (hereafter referred to as BS) and monolithic SiC ceramics with sintering additives of 3 wt% B4C and 3 wt% C (hereafter referred to as S), respectively.

To study effects of other roughness parameters (Rz, Rku, Rsk) and surface morphology on tribological behavior of samples with similar values of Ra parameter, disc type specimens with nominal dimensions of 29 × 26 × 4.5 mm³ were polished to have similar average surface roughness (Ra = 0.01–0.02 μm) using diamond slurry. Surfaces of the three samples were randomly orientated. Different surface morphology and different Rz, Rku and Rsk values were caused for the three samples after polishing. The relative densities of the obtained samples were measured by the Archimedes method. The hardness of the obtained samples were measured by a Vickers hardness instrument. The microstructure of the polished surfaces of the samples was examined by SEM.

Tribological tests were made on a pin-on-disk tribometer under dry sliding contacts at room temperature of 25 ± 2°C. Commercial SiC balls (9.5 mm diameter) were used as counterbodies. The sliding distance for each friction test was set to 100 m, during which the steady state condition were reached. The tests were conducted at speed on 0.1 m/s and under a normal load of 5 N. The relative humidity was about 40–50%. The friction coefficients were monitored as a function of sliding distance during tests. The roughness profiles of the samples were measured by a surface profilometer.

3. Results and discussion

3.1 Physical properties and microstructure analysis

Physical properties of the three samples are shown in Table 1. The sample S shows a slightly higher relative density and the sample BS shows a slightly higher hardness. As a whole, the three samples don’t show obvious difference in physical properties. The representative micrographs of the polished surfaces of B, BS and S are shown in Fig. 2. Visible pores are observed in all the three samples. Compared with sample B and sample BS, less pores are observed in the sample S, which is consistent with the relative densities measurements.

| No. of samples | Relative density (%) | Hardness (GPa) |
|---------------|---------------------|---------------|
| B             | 95.67               | 29.7 ± 2.6    |
| BS            | 97.09               | 30.4 ± 1.2    |
| S             | 98.65               | 27.7 ± 1.0    |

3.2 Surface roughness parameters and surface morphologies

Different surface roughness parameters (Rz, Rku, Rsk) for the three samples are shown in Fig. 3. Typical roughness profiles of the three samples after polishing are shown in Fig. 4. Although Rz shows similar values for the three samples, Rku and Rsk exhibit different behaviors. Among the three samples, the sample BS reveals the largest Rz. The larger Rz is probably attributed to the larger pores formed during the sintering process. As for Rku of the three samples, the values for three samples are 49.60, 26.38 and 5.49, respectively. The Rku parameters of all three samples are greater than 3. As for Rsk of the three samples, the values for the three samples are −5.45, −3.99 and 0.05, respectively. Except for the sample S, the other two samples reveal negative values of Rsk parameter. The value of Rsk parameter of the sample S is ≈0, which is a characteristic of Gaussian distribution. Moreover, in our previous work,12) we discovered that nanorelief structure was formed during polishing for B4C–SiC composite ceramics because of preferential wearing of SiC grains by free diamond particles. The dimple depth is approximately 10 nm after polishing. A schematic diagram for nanorelief structure is shown in Fig. 5. However, the nanorelief structure didn’t be observed on the surface for monolithic ceramics.
3.3 Average coefficients of friction during run-in period

Figure 6 shows the average coefficients of friction of the three samples during run-in period. Figure 7 shows the typical curves of friction coefficients of the three samples. It can be seen that the friction coefficients for the three samples reached a peak value of approximately 1.0 during run-in period, and then decreased to a steady state value. A slightly lower maximum friction coefficient for the sample BS was measured during run-in period. Further, the sample BS reveals the lowest coefficient of friction during run-in period (Fig. 6). In general, the friction coefficient of materials during run-in period is associated with the initial surface roughness. Rubino et al. reported that the B₄C ceramics with different surface roughness (Rₐ = 0.9, 1.3, 1.9 μm) exhibited different friction coefficients during run-in period.¹¹ The B₄C ceramics with higher surface roughness (Rₐ) showed a slightly lower friction coefficient.
Rubino et al. also stated that for SiC ceramics, the SiC ceramics with initial smoother surface \((R_a = 0.5 \, \mu m)\) had a higher friction coefficient than that of the SiC ceramics with initial rougher surface \((R_a = 2.2 \, \mu m)\) during run-in period.\(^{11}\) The friction coefficient is decided by the asperities and protrusion between the two mating surfaces at the beginning of the test. The rougher surface means a lower number of contact points, which needs a smaller force to break these conjunctions. However, in the present study, the three samples have similar surface roughness \((R_a)\) but different surface morphologies. For monolithic ceramics, it is considered that there is no obvious relief structure after polishing, which has been proved in our previous work.\(^{12}\) In contrast, the relief structure with the depth of \(\sim 10 \, \text{nm}\) was observed on the \(\text{B}_4\text{C} - \text{SiC}\) composite ceramics after polishing.\(^{12}\) The formation of nanorelief structure on the \(\text{B}_4\text{C} - \text{SiC}\) composite ceramics, on the one hand, can reduce the real contact area between the two mating surfaces, and on the other hand, can trap wear particles. The reduced real contact area can decrease adhesion effect between the two mating surfaces, which is beneficial to reduce the coefficient of friction. Meanwhile, wear particles can be trapped in the craters of the nanorelief structure. Although the size of wear particles may larger than the depth of the nanorelief structure and the nanorelief structure can’t act as wear particles’ traps to reduce friction directly, which is the function of relief structure produced by laser, the wear particles can be held or fixed on the worn surface by the craters of nanorelief structure and further broken to much smaller pieces. The smaller wear pieces, whose composition may be SiC, \(\text{B}_4\text{C}\) or the mixture of \(\text{B}_4\text{C}\) and SiC, are more easy to be oxidized and lower the coefficient of friction. Conversely, it is difficult for the wear particles to have the same effect on the monolithic \(\text{B}_4\text{C}\) ceramics and the monolithic SiC ceramics during the friction process. The wear particles can move easily and it is hardly for them to stay at the interface during the friction process. Therefore, the sample BS shows the lowest coefficient of friction.

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friction. In addition, Sedlaček et al. suggested that the surface profile of hardened 100Cr6 ball bearing steel with a higher value of $R_{ku}$ and a more negative $R_{sk}$ can cause a lower friction coefficient.13) The sample B has a higher value of $R_{ku}$ and a more negative $R_{sk}$ than those of sample BS, however, the sample B reveals a higher coefficient of friction than that of the sample BS. As a result, it can be concluded that surface morphology may have been a competitive factor for coefficient of friction as compared B$_4$C–SiC composite ceramics with monolithic B$_4$C ceramics. Furthermore, when compared with monolithic SiC ceramics, monolithic B$_4$C ceramics has a higher value of $R_{ku}$ and a more negative $R_{sk}$, resulting in a slightly lower friction coefficient, which is consistent with the result of Sedlaček et al. stated above.

3.4 Sliding distance to steady state condition

Figure 8 shows the sliding distance to steady state condition for the three samples. The characteristic of the steady state condition is that the friction coefficient tends to a constant, and there may be large fluctuations near the constant based on the experimental and material parameters. The sample BS exhibits the shortest sliding distance up to the steady state condition. On numerous occasions, the sliding distance to steady state condition is also associated with the initial surface roughness. Kubiaik et al. reported that friction coefficient evolves more quickly to its stable value for smoother surfaces and then remains at that level during friction processes.14) Sedlaček et al. found that although rougher surfaces have lower friction coefficient, sliding distance when steady state condition is reached, is longer for rougher surfaces.15) In the present study, the three samples have the similar average roughness ($R_s$), however, they also show different sliding distance to steady state condition. Compared with the monolithic ceramics, the B$_4$C–SiC composite ceramics has a different surface morphology. The nanorelief structure is formed on B$_4$C–SiC ceramics. The reduced adhesion and the trap of wear debris resulting from the nanorelief structure make the coefficient of friction quickly to its stable-state. Furthermore, the sample B and the sample S have similar $R_a$ values but different $R_{ku}$ and $R_{sk}$ values. The surface with higher $R_{ku}$ and lower $R_{sk}$ is easier to cause fast run-in period,13) therefore, the sliding distance is shorter for sample B than that for sample S.

Low friction coefficient during run-in period and short sliding distance to steady state condition in unlubricated sliding can result in expansion of the sphere of application of ceramic tribo-elements. Friction is related with the energy consumption. Low friction coefficient during run-in period and short sliding distance to steady state condition mean the decrease in heat generation, which can provide an opportunity to reduce the requirements for the heat transfer. The nanorelief structure formed in situ is used to change the surface morphology, and subsequently to change tribological performance of ceramic. In recent
years, the research of ceramics on tribology is not only to improve tribological performance, but also to improve the strength and reduce the cost of manufacturing. Unlike laser-fabricated relief structure, nanorelief structure formed in situ would not reduce the strength of ceramics due to the absence of defects caused by laser. On the other hand, the cost of nanorelief structure formed in situ is significantly lower than that of laser-fabricated relief structure. However, nanorelief structure formed by in-situ method is confined to composite ceramics at present, whilst nanorelief structure can’t be formed in situ on all composite ceramic surfaces. Further research should be focused on the study of the effects of surface roughness parameters and surface morphology on the wear of ceramics during run-in period.

4. Conclusions

In this paper, pin-on-disc tests with B4C disc, B4C–SiC disc and SiC disc with SiC balls were carried out to study the influence of surface morphology and surface roughness parameters on tribological behavior on the basis of the samples with similar surface roughness (Rz). The main conclusions are as follows:

(1) For friction coefficient during run-in period in dry sliding, surface morphology is considered as a more important competitive factor. The friction coefficient during run-in period for B4C–SiC composite ceramics with nanorelief structure on the surface is lower than those for monolithic B4C ceramics and monolithic SiC ceramics, both of which have no nanorelief structure. Compared with the monolithic SiC ceramics, the monolithic B4C ceramics with a higher Rku and a more negative Rsk results in a slightly lower friction coefficient.

(2) For sliding distance to steady state condition in dry sliding, surface morphology also plays an important role. The B4C–SiC composite ceramics with nanorelief structure on the surface exhibit the shortest sliding distance up to steady state condition. Compared with the monolithic SiC ceramics, the monolithic B4C ceramics with a higher Rku and a more negative Rsk leads to a shorter sliding distance up to steady state condition.

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References

1) S. Gupta, S. K. Sharma, B. V. M. Kumar and Y. W. Kim, Ceram. Int., 41, 14780–14789 (2015).
2) X. Q. Li, Y. M. Gao, S. Z. Wei, Q. X. Yang and Z. C. Zhong, Ceram. Int., 43, 162–166 (2017).
3) W. Zhang, S. Yamashita and H. Kita, Adv. Appl. Ceram., 118, 222–239 (2019).
4) W. Chen, Y. M. Gao, C. Chen and J. D. Xing, Wear, 269, 241–248 (2010).
5) H. Kita, K. Osumi, T. Iizuka, M. Fukushima, K. Yoshida and H. Hyuga, J. Ceram. Soc. Jpn., 114, 599–602 (2006).
6) L. Q. Kong, Q. L. Bi, M. Y. Niu, S. Y. Zhu, J. Yang and W. M. Liu, J. Eur. Ceram. Soc., 33, 51–59 (2013).
7) F. Li, S. Y. Zhu, J. Cheng, Z. H. Qiao and J. Yang, Tribol. Int., 111, 46–51 (2017).
8) Z. S. Chen, H. J. Li, Q. G. Fu and X. F. Qiang, Tribol. Int., 56, 58–65 (2012).
9) J. R. Jiang and R. D. Arnell, Wear, 239, 1–9 (2000).
10) C. Y. Chen, B. H. Wu, C. J. Chung, W. L. Li, C. W. Chien, P. H. Wu and C. W. Cheng, Tribol. Lett., 51, 127–133 (2013).
11) F. Rubino, M. Pisaturo, A. Senatore, P. Carlone and T. S. Sudarshan, J. Mater. Eng. Perform., 26, 1–12 (2017).
12) W. Zhang, S. Yamashita, T. Kumazawa, F. Ozeki, H. Hyuga and H. Kita, Ceram. Int., 45, 13818–13824 (2019).
13) M. Sedlaček, B. Podgornik and J. Vižintin, Tribol. Int., 48, 102–112 (2012).
14) K. J. Kubiak, T. W. Liskiewicz and T. G. Mathia, Tribol. Int., 44, 1427–1432 (2011).
15) M. Sedlaček, B. Podgornik and J. Vižintin, Wear, 266, 482–487 (2009).