Friction and wear characteristics of silicon nitride ceramics under dry friction condition

Jinmei Yao, Yuhou Wu, Jian Sun, Junxing Tian, Peng Zhou, Zhigang Bao, Zhongxian Xia and Longfei Gao

School of Mechanical Engineering, Shenyang Jianzhu University, Shenyang 110168, People’s Republic of China
School of Mechanical Engineering, Tsinghua University, Beijing 100084, People’s Republic of China

E-mail: sunjian09edu@sina.com

Abstract
In order to reveal the friction properties and improve the wear resistance of silicon nitride ceramic materials, a calculation model of static friction coefficient of silicon nitride ceramic is established. The influence law of contact surface roughness on friction coefficient under different contact load and friction speed is analyzed. The test and the results verification are carried out by using Friction Wear Testing Machine. Then the dry friction process of silicon nitride ceramic is simulated based on UDEC, and the wear failure form is analyzed. In the dry friction process of silicon nitride ceramics, the coefficient of friction is directly proportional to the contact surface roughness, inversely proportional to the contact load, and directly proportional to the friction speed. There is a critical value for the roughness of friction sub-contact surface. Silicon nitride ceramics can self-lubricate by friction when the contact surface roughness is less than this critical value. In the dry friction process, the oxidation of SiO2 has little effect on the friction. The wear surface of silicon nitride ceramics consists of shear failure units and tensile failure units, and their formation is related to the surface roughness. The results play an important role in revealing the frictional properties of engineering ceramics such as silicon nitride, as well as helpful to improve the wear resistance and service life of ceramic materials.

1. Introduction

The engineering ceramics represented by silicon nitride ceramics has the advantages of high elastic modulus, low density, high temperature resistance, corrosion resistance and high hardness [1, 2]. It has gradually become an indispensable key material for cutting-edge technology. Countries all over the world regard it as a new high-tech material that has a significant impact on the development of human society [3–5]. Due to the particularity of materials, silicon nitride ceramics are more and more widely used in high-end fields, such as bearings and seals [6, 7]. Therefore, the study on the friction performance of silicon nitride ceramics has become one of the hot spots and frontiers. Manzoor Shahid, Qin Wenbo and Yeo Reuben et al have done a lot of researches on the frictional wear and machine rationality of hard brittle materials [8–11]. The following conclusions are mainly formed: (1) under the dry friction, the ceramics mainly break, crack and break, and then cause the wear of the grinding grain. Under the lubrication condition, it mainly appears in the frictional chemical wear. (2) In the case of low contact load and sliding speed, the wear mechanism is sticky and peeling. When the contact load and sliding speed are high, the ceramic wear surface would melt. The melted part falls off during friction and solidifies into flake debris after cooling. (3) Non-oxide ceramics may experience frictional oxidation and wear of the oxide layer [12–20]. Sun Jian analyzed the factors that affect the surface quality of silicon nitride ceramics. It has found that between friction depth and speed, the latter factor has a greater impact on friction force and the quality of surface [21, 22]. The frictional wear performance of ceramics is influenced by the nature of materials, the environmental conditions, the pairing friction materials and more. However, there is no universal mechanism to explain the frictional wear of all ceramics. In addition, there are few studies on the factors
affecting the surface quality of silicon nitride ceramics, especially the influence of surface roughness on the frictional properties of silicon nitride. In fact, the frictional behavior of silicon nitride ceramic is very sensitive to surface roughness, which has a great effect on the friction factor and wear performance of ceramics.

In this paper, the methods of theoretical calculation and experimental verifications are used. By analyzing the frictional sub-contact on the processing surface of silicon nitride ceramics, the relationship between static friction coefficient and surface roughness is obtained from the Florida model. Under the dry friction at room temperature, comprehensive friction tests were carried out on silicon nitride ceramics with different surface roughness. The wear surface morphology and wear debris of the specimen were analyzed by scanning electron microscope to understand the friction process of ceramic materials. The frictional wear mechanism of silicon nitride ceramics and its influence on surface quality are revealed. It provides a favorable basis for accumulating and perfecting the tribology properties of silicon nitride ceramic materials.

2. The calculated model of static friction coefficient of silicon nitride ceramics

When the two surfaces of silicon nitride ceramics contact each other, only a few rough peaks contact on the surface due to the influence of surface roughness, and the contact points are also discrete. Therefore, the actual contact area is only a small part of the nominal contact area, and the applied load is mainly borne by these small rough peaks. The rough peaks of contact would change accordingly when the roughness of one of the contact surfaces changes. Therefore, the coefficient of static friction also changes with the surface roughness. In order to study the relationship between the static coefficient of friction and surface roughness, the contact model of rough surface should be established first.

The Florida model is shown in figure 1, which shows that the friction sub-interactions appear in the process of relative motion. It includes the ploughing effect and adhesion of rough peak as well as the effect of tear debris sliver on the surface after friction sub-wear in the process of friction.

It can be seen from figure 1 that the coefficient of static friction between the friction subs is as follows:

\[ \mu = (1 - \beta)\mu_a + \mu_{ap} + \beta \mu_d \]

Where, \( \mu_a \) is the adhesion part of rough peak in the static friction coefficient; \( \mu_{ap} \) is the action part of rough peak ploughing in the static friction coefficient, \( \mu_d \) is the action part of the grinding debris ploughing in the static friction coefficient; \( \beta \) is the percentage of rough peak effect in the static friction coefficient of rough peak ploughing, and the value of silicon nitride ceramic materials is 1.

When only the ploughing and adhesion of rough peak are considered, the static coefficient of friction is:

\[ \mu = (1 - \beta)\mu_a + \beta \mu_{ap} \]

According to the existing relationship between friction and stress-strain, it can be obtained:

\[ \mu_a = \frac{A_a}{P} \left[ \frac{\tau_{a1}}{\sigma_1} f \left( \frac{\tau_{a1}}{\sigma_1} \right) + \frac{\tau_{a2}}{\sigma_2} f \left( \frac{\tau_{a2}}{\sigma_2} \right) \right] \]

Where, \( \tau_{a1} \) and \( \tau_{a2} \) are the adhesion shear stresses of contact materials; \( \sigma_1 \) and \( \sigma_2 \) are the shear strength of the material; \( A_a \) is the actual contact area formed by rough peaks, and \( P \) is the total load in the vertical direction.

\[ \mu_{ap} = \frac{A_a}{P} \left[ \sigma_1 + \sigma_2 f \left( \frac{\sigma_1 H_1}{\sigma_2 H_2} \right) \right] \]
Where, $H_1$ and $H_2$ are the hardness of the material.

$$f(t) = 1 - \left[ \frac{2 \ln (1 + t) - t}{\ln (1 - t^2)} \right]$$

Substituting equations (3) and (4) into (2), it can be obtained that:

$$\mu = (1 - \beta) \frac{A_0}{P} \left[ \sigma_{t1} f \left( \frac{\tau_{t1}}{\sigma_{t1}} \right) + \sigma_{t2} f \left( \frac{\tau_{t2}}{\sigma_{t2}} \right) \right] + \beta \frac{A_0}{P} \left[ \sigma_{t1} + \sigma_{t2} f \left( \frac{\sigma_{t1} H_1}{\sigma_{t2} H_2} \right) \right]$$

$A_0$ can be obtained based on Hertz theory [24]:

$$A_0 = \pi \sigma D_0 A_0 F_1 \left( \frac{d}{\sigma} \right)$$

$$F_1 \left( \frac{d}{\sigma} \right) = \frac{1}{\sqrt{2\pi \sigma}} \int_0^\infty \left( x - \frac{d}{\sigma} \right) e^{- \frac{x^2}{2\sigma^2}} dx$$

$$d = 4.1 R_0 \left( \frac{P_c}{P_r} \right)^{1/2}$$

Where, $r$ is the average radius of the spherical rough peak; $\sigma$ is the conversion value of the standard deviation for the height of rough peak; $D_0$ is the number of spherical rough peaks on the unit area; $A_0$ is the nominal contact area; $d$ is the separation distance of the rough peak reference plane of friction surface; $p_c$ is the contour contact pressure, and $p_r$ is the actual contact pressure.

Substituting equations (7) into (6), the correlation between the surface roughness of silicon nitride ceramics and the coefficient of friction can be obtained.

3. The test device and method

The instrument used in the test is Rtec Friction Wear Testing Machine made in the United States. Its load range is 1 $\mu$N – 2000 N, and reciprocating motion range of the carrier is 30 mm. The high-speed linear reciprocating motion frequency is 70 Hz, and the range of ambient cavity temperature is $-120 \degree C$–$1000 \degree C$. The test device and its principle are shown in figure 2.

Taking silicon nitride ceramic friction as the research object, hot isostatic pressing method is used to prepare silicon nitride ceramic materials. The sintering temperature is 2000 $\degree$C; the holding time is 60 min; the sintering pressure is 200 MPa, and the sintering aid is Al$_2$O$_3$. The physical properties of the sample are shown in table 1.

The specimen 2 in figure 2(b) is machined as $25 \times 5$ mm. The pre-test wear surface of specimen 2 is polished to the mirror with a diamond grinding wheel on the precision plane grinder named BLOHM Orbit 36. This pair is a silicon nitride ceramic ball of the same material, which is the ground on a ball rubbing machine named 3ML4780D. The diameter of the ball is $9.525 \text{ mm}$ and the spherical error is less than 0.0025 mm.

Specimen 1 is placed on the surface of specimen 2 under the action of legal load, and specimen 2 will make high-speed linear reciprocating motion within 20 mm shown as figure 2(b).

Before and after the test, all specimens are cleaned with acetone ultrasonic for 15 min, and the dryer is placed in the dish for drying.

The test is carried out at no lubricated room temperature. The friction and wear test system automatically records each test, and the temperature test system records the temperature change in real time. The surface wear...
Table 1. Physical properties of silicon nitride ceramics.

| Property                                      | Value                                      |
|-----------------------------------------------|--------------------------------------------|
| Density (g cm\(^{-3}\))                      | 3.07–3.21                                  |
| Hardness (kg mm\(^{-2}\))                    | 1520                                       |
| Bending strength (MPa)                        | 1200                                       |
| Compressive strength (MPa)                    | 4500                                       |
| Thermal expansion coefficient (10\(^{-6}\)/°C) | (20 °C–1000 °C) 3.5–3.9                    |
| The Young’s modulus (GPa)                     | (20 °C) 310                                |
| Poisson’s ratio (20 °C)                       | 0.27                                       |
| Fracture toughness (MPa m\(^{1/2}\))         | 7–12                                       |
| Heat conductivity (W m\(^{-1}\)K)            | 20                                         |
| Specific heat capacity (J Kg\(^{-1}\)K)       | 711.756                                    |
morphology of silicon nitride ceramics is observed by Hitachi s-4800 scanning electron microscope, including grain shedding, micro-cracks and plastic deformation.

Using single factor test method, four groups of tests are carried out on the contact load, the friction speed and the friction contact surface roughness. Silicon nitride ceramic friction pair is ceramic ball and ceramic plate shown as figure 2(b). The roughness of the surface of the ceramic ball is divided into G3, G5, G10, G16 and so on according to the standard grade shown as [25] from high to low. Therefore, the contact surface roughness of friction pair in the experiment is selected according to the standard. The test time for each group is 10 min. The test parameters and levels are shown in table 2.

### Table 2. Test parameters and levels.

| Group | Friction speed \(v\) (m min\(^{-1}\)) | Contact load \(F\) (N) | Roughness of friction contact surface \(Ra\) (\(\mu m\)) [25] |
|-------|-----------------------------------|------------------------|--------------------------------------------------|
| 1     | 20                                | 20, 40, 60, 80, 100, 120, 140, 160 | 0.01 (G3), 0.014 (G5), 0.02 (G10), 0.025 (G16), 0.032 (G20), 0.04 (G24) |
| 2     | 40                                |                        |                                                  |
| 3     | 60                                |                        |                                                  |
| 4     | 80                                |                        |                                                  |

4. Testing results and analysis

#### 4.1. Influence of different conditions on friction coefficient of silicon nitride ceramics

The variation of friction coefficient of silicon nitride ceramics with contact load, friction speed and contact surface roughness under dry friction at room temperature is shown in figure 3. Compared with the four pictures in figure 3, it can be concluded that the smaller the contact surface roughness, the larger the contact load, the smaller the friction speed, and the smaller the friction coefficient of silicon nitride ceramics. Among the above factors, surface roughness has the greatest influence on the friction coefficient, while the friction speed has the least effect. In the range of test data, when the value of \(R_a\) is 0.01 \(\mu m\), \(F\) is 160 N and \(v\) is 20 m min\(^{-1}\), the minimum value of silicon nitride friction coefficient \(\mu\) is 0.025 \(\mu m\). When \(R_a\) is 0.04 \(\mu m\), \(F\) is 20 N and \(v\) is 80 m min\(^{-1}\), the minimum value of \(\mu\) is 0.889 \(\mu m\). Furthermore, when the contact surface roughness is less than 0.014 \(\mu m\), regardless of the contact load and friction speed, the friction coefficient of silicon nitride is always in the small range of 0.025–0.048 \(\mu m\), and the change is basically the same. This shows that when the contact surface roughness is less than a certain value, the friction coefficient of silicon nitride ceramics is not affected by external factors, which can achieve self-lubrication of friction.

#### 4.2. Analysis of the wear surface morphology of silicon nitride ceramics

The dry friction surface wear morphology of silicon nitride ceramics under different conditions is shown in figure 4. In order to reveal the friction characteristics and wear of silicon nitride ceramics, a large number of experiments were done. Then, typical test results were selected under 4 operating conditions. The friction coefficient in figure 4(a) is measured, and the value of \(\mu\) is 0.037 \(\mu m\). It can be seen that its surface is very smooth without visible scratches. Thus when the surface roughness of silicon nitride is less than 0.014 \(\mu m\), dry friction has no effect on its surface, and the friction characteristics of ceramics are ideal. The friction coefficient measured in figure 4(b) is 0.426 \(\mu m\). There are friction scratches on the surface, which destroys the processed surface morphology of silicon nitride. The value of friction coefficient is 0.031 \(\mu m\) measured in figure 4(c) and the cracks are visible on its surface. This is because the surface of figure 4(c) has a roughness of \(R_a = 0.014 \mu m\) and the surface quality is good. However, due to the high contact load and friction speed, a small amount of thermal crack will appear on the surface of silicon nitride ceramics under dry frictional conditions, which has no effect on the surface friction coefficient. The value of friction coefficient is 0.891 \(\mu m\) measured in figure 4(d). Because of the large roughness, the surface is poor. At the same time, under the action of large contact load, the wear phenomenon of friction surface is more obvious and fatigue wear appears.

#### 4.3. Chemical composition of the friction surface of silicon nitride

The surface chemical composition of silicon nitride ceramics after friction test is analyzed as shown in figure 5. The chemical composition of the silicon nitride surface is detected before test as shown in figure 5(a). It can be seen from the test results that the pre-test part is composed of silicon nitride and contains a small amount of Al2O3 sinter agent. After the friction test, the chemical composition analysis of the grinding debris on the wear surface of silicon nitride is shown in figures 5(b) and (c). From the results, it can be seen that the components of grinding debris are mainly SiO2 and Al2O3. Among them, SiO2 is a newly produced substance. In addition,
combined with the chemical composition of the specimen surface after friction test in figure 5(d), it can be obtained that the chemical composition of the worn surface is basically silicon nitride and contains a small amount of Al₂O₃. There are no new substances produced after dry friction of silicon nitride in figure 5(d). It

Figure 3. The variable law of friction coefficient of silicon nitride ceramic.
Figure 4. Friction wear surface morphology of silicon nitride ceramic.

(a) $R_a=0.014\mu m$, $F=40N$, $v=40m/min$

(b) $R_a=0.04\mu m$, $F=100N$, $v=60m/min$

(c) $R_a=0.14\mu m$, $F=2000N$, $v=100m/min$

(d) $R_a=0.68\mu m$, $F=2000N$, $v=20m/min$

Figure 5. Chemical composition analysis of the friction surface of silicon nitride ceramics.

(a) before the friction test

(b) grinding debris 1

(c) grinding debris 2

(d) after the friction test
shows that silicon nitride ceramic dry friction does not necessarily produce SiO₂. Under certain friction conditions, dry friction of silicon nitride ceramics may also not change the material content. Comparing the four images before and after the experiment in figure 5, it can be seen that the new substance SiO₂ is oxidized under the dry friction of silicon nitride. However, SiO₂ is a silicon oxide that has no lubrication properties and cannot be used as a friction lubricant. Therefore, when the contact surface roughness of silicon nitride ceramic is less than 0.014 μm, the self-lubricating will appear. This process is not due to the new lubrication material being generated during friction, but entirely dependent on the physical properties of silicon nitride and the finish on its surface.

5. Friction and wear simulation analysis of silicon nitride ceramics

5.1. The simulation models

In this paper, UDEC two-dimensional discrete unit method is used to simulate the wear of silicon nitride ceramic surface during dry friction [26]. When the method is used for numerical simulation, it mainly includes block generation, material generation, boundary condition simulation, and load and speed application. Among them, the physical model is mainly established through the formation of blocks and materials as well as the simulation of boundary conditions. The simulation of the motion process is mainly completed by the application of load and speed.

The ceramic friction pair is defined as a deformable body, the initial separation state between deformation bodies is realized by the CELL command, and the material parameters are assigned to the deformable body according to table 1. In order to effectively compare with the results, the simulation boundary conditions are completely consistent with the experimental factors, and the target dimensions of the simulation process are set according to the actual size of test parts. The physical model of silicon nitride ceramic friction pair has been established as shown in figure 6.

A certain initial condition is applied to the friction pair of silicon nitride ceramics, including the vertical load and moving speed. The simulation material is given a certain value to normal stiffness and shear stiffness, and the mechanical effect between the friction pair of ceramic block is realized. The Mohr-Coulomb guidelines, as corrected in UDEC, are used in the model shown as figure 7 [27, 28]. The yield criterion of Mohr-Coulomb is indicated by \( f^s \) in figure 7.

\[
\begin{align*}
    \sigma' &= \sigma_1 - \sigma_3 N_\phi + 2b \sqrt{N_\phi} \\
    N_\phi &= \frac{1 + \sin \phi}{1 - \sin \phi}
\end{align*}
\]

Where, \( \sigma_1 \) is the first primary stress; \( \sigma_3 \) is the third primary stress; \( b \) is the sticky force and \( \phi \) is the friction angle.

The tensile yield criterion is indicated by \( f^t \).

\[
\begin{align*}
    f^t &= \sigma' - \sigma_3
\end{align*}
\]

Where, \( \sigma' \) is the tensile strength.

The numerical simulation results of UDEC provide an intuitive representation of surface wear of silicon nitride ceramics under dry friction. It is also possible to observe and calculate the ceramic wear failure pattern, the unit area ratio of ceramic plastic destruction, the crack expansion and more.
5.2. Analysis of the simulation results

As non-oil self-lubricating, the wear simulation results of silicon nitride ceramics under different friction conditions are shown in figure 8. It can be seen that the surface of silicon nitride ceramics is wore after friction. The wear failure unit consists of shear failure unit and tensile failure unit. Comparing the simulation results in figure 8, it can be seen that when the surface roughness of silicon nitride ceramics is less than 0.014 μm, the amount of friction surface failure unit is less, and the surface wear is basically the same. The wear condition is not affected by the external friction conditions. When the value of surface roughness is greater than 0.014 μm, the surface wear becomes more serious with the increase of the contact load and friction speed. When the value of contact surface roughness of silicon nitride is less than 0.02 μm, the wear surface is mainly shear failure unit. Conversely, the wear surface is dominated by tensile failure units. When the surface roughness is about 0.02 μm, the number of shear and tensile failure units is basically the same. As shown in figures 8(g)–(l), when the value of contact surface roughness increases gradually from 0.025 μm, the failure unit begins to expand from the contact surface to the interior of the ceramics, and the expansion process of the failure unit is the formation process of frictional thermal crack. Meanwhile, it can be seen that in the process of the failure unit of ceramic material from friction surface to internal expansion, the tensile failure unit gradually changes to shear failure unit. It can also be seen from figures 8(g)–(l), when the value of surface roughness is constant, the contact load and friction speed increases, and the surface wear would be more serious. However, the wear failure unit does not extend to the interior of the ceramics in the form of cracks. When the value of contact load and friction speed is constant, the surface roughness increases, the surface wear would also be more serious, and the wear failure unit would extend to the interior of the ceramics.

6. Discussion

When the contact surface roughness of silicon nitride ceramic friction pair is less than 0.014 μm, the contact load and friction speed will not affect the friction and wear process of the ceramics, and self-lubrication can be realized. When the surface roughness is greater than 0.014 μm, the wear of the ceramic surface is greatly affected by the contact load and friction speed. The surface wear is more serious with the increase of the contact load and friction speed under dry friction. This shows that there is a critical value in the contact surface roughness of silicon nitride ceramics in the process of dry friction, and its value is 0.014 μm. This is consistent with the experimental and theoretical research results.

From the experimental and simulation results, they are concluded that the friction coefficient is inversely proportional to the contact load when other conditions remain unchanged in the process of dry friction. From simulation results, it is concluded that the surface wear after friction is proportional to the contact load. Under the large contact load, the wear of contact surface is obvious, and the surface fatigue wear appears. This shows that the friction coefficient of silicon nitride ceramics will decrease if the contact load continues to increase during fatigue wear. The above phenomena can be derived from both experimental and simulation studies. This shows that the theory is consistent with the results of the experiment.

When the surface roughness of silicon nitride ceramics is low, the main phenomenon in the friction process is shear failure. In the friction process with higher roughness, the main phenomenon is tensile wear. This shows that when the surface roughness is small, the extrusion effect would appear between smooth friction surfaces under large load and high-speed friction. It causes shear failure of the material. When the roughness of the
contact surface is large, the scratching and tearing effect in the friction is more obvious, and the surface wear is serious. The failure unit is mainly tensile, and a large number of cracks formed on the surface begin to expand into the interior of the ceramics. In the process of expansion in the form of cracks, the failure unit will change under the thermal stress of frictional high temperature. At the same time, under the brittle extrusion of silicon nitride ceramics, the tensile failure gradually transforms into the shear failure unit.

Figure 8. The results of friction simulation of silicon nitride ceramics based on UDEC.
7. Conclusion

(1) In the dry friction process of silicon nitride ceramics, the friction coefficient is directly proportional to the contact surface roughness, inversely proportional to the contact load, and in proportional to the friction speed. The influence of contact surface roughness on the friction coefficient is the largest, and the friction speed is the least.

(2) There is a critical value in the contact surface roughness of silicon nitride ceramics in the process of dry friction, and its value is 0.014 μm. When the contact surface roughness is less than this critical value, the friction coefficient varies in a small range regardless of the contact load and friction speed. Depending on the physical properties and surface finish of the material, frictional self-lubrication can be produced. (3) The wear debris is oxidized to produce a new SiO2. However, it has no effect on the dry friction process of silicon nitride ceramics. (4) The wear surface of silicon nitride ceramics consists of the shear failure units and tensile failure units. When the contact surface roughness is small, the wear of ceramics is mainly shear failure. Conversely, the tensile failure is the main one. When the failure unit expands from the contact surface to the interior in the form of cracks, the number of shear failure units increases gradually with the increase of expansion depth.

Acknowledgments

The authors acknowledge the collective support granted by National Natural Science Foundation of China (Grant No 51975388), Innovation Team Project of Ministry of Education of China (Grant No IRT_15R45), Department of Science and Technology of Liaoning Province (Grant No 2019-ZD-0666, 2020-BS-159) and Science and Technology Program of Shenyang (Grant No F16-205-1-15).

ORCID iDs

Jian Sun https://orcid.org/0000-0002-4586-633X

References

[1] Zhang Y, Zhao M, Zhang I, Shao Q, Li J, Li H and Guo Z 2018 Excellent corrosion protection performance of epoxy composite coatings filled with slane functionalized silicon nitride J. Polym. Res. 25 1–13
[2] Wu J-M, Ma Y-X, Chen Y, Cheng L-J, Chen A-N, Liu R-Z and Lin J-P 2019 Preparation of Si3N4 ceramics by aqueous gelcasting using non-toxic agar powder as gelling agent without cooling crosslink process Ceram. Int. 45 20961–6
[3] Zhang X-H, Wen D-D, Deng Z-H, Li S, Wu Q-P and Jiang J 2018 Study on the grinding behavior of laser-structured grinding in silicon nitride ceramic Int. J. Adv. Manuf. Technol. 96 3081–91
[4] Hameiri Z, Borovic Z, Mai L, Nandakumar K, Kim K and Winderbaum S 2017 Low-absorbing and thermally stable industrial silicon nitride films with very low surface recombination IEEE J. Photovolta. 7 996–1003
[5] Lan A, Liu C-E, Yang H-L, Yu H-T, Liu I-T, Hsu H-P and Lan C-W 2019 Silicon ingot casting using reusable silicon nitride crucibles made from diamond wire sawing kerf-loss silicon J. Cryst. Growth 525 123184
[6] N M and G R 2017 Effect on lubrication regimes with silicon nitride and bearing steel balls Tribol. Int. 116 403–13
[7] Yang H, Zheng P, Hu G, Zhang R, Yun B and Cui Y 2019 A broadband, low-crosstalk and low polarization dependent silicon nitride waveguide crossing based on the multimode-interference Opt. Commun. 450 28–33
[8] Manzoor S, Wani M F and Saleem S S 2019 Effect of load on the friction and wear behaviour of silicon nitride and silicon nitride titanium carbide ceramic composite Mater. Today Proc. 19 474–7
[9] Qin W, Yue W and Wang C 2018 Controllable wear behaviors of silicon nitride sliding against sintered polycrystalline diamond via altering humidity J. Am. Ceram. Soc. 101 2586–15
[10] Radhika N 2018 Comparison of the mechanical and wear behaviour of aluminium alloy with homogeneous and functionally graded silicon nitride composites Science and Engineering of Composite Materials 25 261–71
[11] Yeo R J, Dwivedi N, Zhang Z, Lim C Y H, Tripathy S and Bhatia C S 2017 Superior wear resistance and low friction in hybrid ultrathin silicon nitride/carbon films: synergy of the interfacial chemistry and carbon microstructure Nanowale 9 14937–51
[12] Xing Y, Deng J, Wu Z and Wu F 2017 High friction and low wear properties of laser-textured ceramic surface under dry friction Opt. Laser Technol. 93 24–32
[13] Chengmin W, Xuefeng X, Xiguang C, Tao M, Yunxi L and Peilong S 2017 Friction and wear properties of an automobile brake lining reinforced by lignin fiber and glass fiber Industrial Lubrication and Tribology 69 773–81
[14] Cheng F, Liu J P and Liang Y F 2019 Friction and wear properties of a high Nb-containing TiAl alloy against WC-8Cr, Si3N4, and GCr (15) in an unlubricated contact Intermetallics 106 7–12
[15] Shpenev A G 2018 Friction and wear of fiber composites with abrasive particles on contact surface J. Frict. Wear 39 188–94
[16] Yang K, Shi X, Huang Y, Liu X and Wang Y 2017 A study of the friction layer of TiAl-10 wt.% Ag composite and the prediction model of friction and wear behaviors Proc. Inst. Mech. Eng. Part J Eng. Tribol. 232 699–710
[17] Li L, Kang L, Ma S, Li Z, Ruan X and Cai A 2018 Finite unit analysis of fretting wear considering variable coefficient of friction Proc. Inst. Mech. Eng. Part J Eng. Tribol. 208–210 135065011880061
[18] Li Y-M, Yue Q-B, Li H-Y and He H-B 2018 Friction and wear characteristics of 20Cr steel substrate and TiAlN coating under different lubrication conditions Int. J. Precis. Eng. Manuf. 19 1321–8
[19] Xue B, Ma W and Liu Y 2018 Friction and wear behavior of TiAl matrix composites incorporated with silver and molybdenum disulfide J. Mater. Eng. Perform. 27 4176–82
[20] Amirjan M 2018 Microstructure, wear and friction behavior of nanocomposite materials with natural ingredients Tribol. Int. 131 184–90
[21] Sun J, Wu Y H, Zhou P, Li S H, Zhang L X and Zhang K 2017 Simulation and experimental research on Si₃N₄ ceramic grinding based on different diamond grains Adv. Mech. Eng. 9 1–12
[22] Sun J, Wu Y H, Zhou P, Li S H, Zhang L X and Zhang K 2018 Research on the cracks extending mechanism of grinding silicon nitride ceramics Revista Romana De Materiale - Romanian Journal of Materials 48 198–203
[23] Xie T, Chen K, Zhou Z and Yang H 2019 Numerical simulation of the dynamic evolution of the friction interface of PTFE/45 steel friction pair Mater. Res. Express 6 105338
[24] Pozharskii D A 2018 Contact of transversely isotropic bodies in the hertz theory J. Appl. Mech. Tech. Phys. 59 491–7
[25] 2008 ISO 3290-2: 2008, IDT, Rolling bearings-Balls-Part 2: Ceramic balls (2008).
[26] Mayer JM and Stead D 2017 Exploration into the causes of uncertainty in UDEC grain boundary models Comput. Geotech. 82 110–23
[27] Gao W, Xiao T, Wang X and Wang C 2019 Theoretical study on extension of crack tip plastic zone by remote simple tensile considering crack interaction Eur. J. Mech. A. Solids 77 103814
[28] Yang C-P and Jia F 2018 Crack opening model for unidirectional ceramic matrix composites at elevated temperature Ceram. Int. 44 17167–73