

Comparison of 4-ball and 5-ball rolling contact fatigue tests on lubricated Si₃N₄/steel contact

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Abstract: Accelerated 4-ball and 5-ball rolling tests were performed on HIPed Si₃N₄ ball samples (rough lapped with surface roughness value R_a 0.08 μm and R_q 0.118 μm) in fully lubricated condition. The contact load and the stress cycles per minute for 4-ball rolling and 5-ball rolling tests were maintained the same. The rolling track appearances of 5-ball tests reveal severe sliding occurred. In one case, the opposite arc cracks were generated all over the two sides of the rolling track, and this could not be explained by simplified kinematics model. The failure mechanisms were discussed, which suggest the sliding on the two sides of the track was in opposite direction.

Key Words: engineering ceramics (A), fatigue (E), failure analysis (H)

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1. Introduction

Current demands on load bearing contacts in all kinds of machinery are leading to the developments aimed at running them at high speeds, hostile environments, increased unit loads and restricted lubrication. Hot Isostatically Pressed (HIPed) Si_3N_4 rolling elements have the optimum combination of properties (low density, high elastic modulus, good corrosion resistance and temperature resistance, low friction coefficient) [1] to meet such demands for the application in hybrid (with steel inner and outer rings) and all ceramic precision ball bearings. Since these rolling elements are subjected to high cyclic contact stresses during service, the Rolling Contact Fatigue (RCF) life is major concern.

Since rolling contact fatigue failure is probabilistic, statistical procedures have been established for the analysis of bearing fatigue life. A “rating” life system has been defined using two specific points on the failure distribution curve. These points are the L_{10} life, or the life that 90% of the bearings can be expected to survive, and the L_{50} life, which 50% of the bearings can be expected to exceed. Full-scale bearing endurance tests were conducted on bearing life test rigs by many bearing manufacturers and research institutes. Because numerous test samples are required to obtain a usable experimental life estimate, conducting full-scale endurance test is very expensive. The identification of a simpler, less costly, life testing methods (the use of element testing configuration) has therefore been a longstanding goal [2].

To date, there are a few different types of RCF testers commonly used for measuring RCF life. Among them is the Disk-on-Disk (Cylinder-on-Cylinder, Ring-on-Ring) tester [3], which can be used to assess the rolling element materials but not appropriate to fit rolling element ball samples directly. The RCF testers which can directly assess rolling element ball samples are Three-Ball-on-Rod tester [4], Rolling-Element-on-Flat tester [5], V-Groove/Ball tester [6], Four-Ball-Rolling tester [7] and Five-Ball-Rolling tester [8]. None of the RCF testers can reproduce the complex test conditions encountered in a full-scale bearing test. The advantage of accelerated element testing on a RCF tester is being able to reveal the failure mechanism and the factors which influence the failure in a minimum number of tests. Because of the difference in test configurations, the different RCF testers may lead to very different testing results. In this paper, Four-Ball-Rolling and Five-Ball-Rolling configurations are used to test HIPed Si_3N_4 rolling element ball samples to assess the influences of test configurations.

2. Experiment

2.1 Test Machine & Si_3N_4 Samples

Rolling contact fatigue tests were conducted on a Plint TE 92 HS 10,000 rev/min Microprocessor Controlled Rotary Tribometer (Fig 1). A full description about this tribometer can be found in a previous publication [9]. In this research, it was configured to run 4-ball and 5-ball rolling contact fatigue tests. Through a computer interface, the test speed, load, temperature, etc. were controlled by editing values, ramps and steps in the menu. During the test, the test speed, load, temperature, etc. were recorded to a computer file. The test will be stopped after a pre-set number of revolutions of the driving-shaft as measured by a counter. If the upper ball or the lower balls failed during testing the machine would vibrate, and a vibration sensor automatically stops the test at a pre-determined sensitivity. The contact region between the upper ball and lower balls is immersed in lubricating oil during each test. The lubricant oil is a base mineral oil with kinematic viscosity (cSt) 94.6 at 40 °C and 8.8 at 100 °C.

The lower balls are standard steel testing balls (specification: 0.5" ball Reference RB12.7/310995A, material: AISI 52100 bearing steel). The measured geometric and physical properties of the steel test balls are listed in Table 1. The upper ball is the HIPed Si_3N_4 specimen ball. The test Si_3N_4 samples for this investigation were rough lapped by the authors using an eccentric lapping machine [10]. It was anticipated that the traction between 4-ball test and 5-ball test would be different, and this will be best revealed by a rougher surface. The measured geometric and physical properties are listed in Table 2. Fig.2 shows 3D topographic measurement (a) and microscopy observation (b) of the Si_3N_4 test sample surface.

2.2 Rolling Contact 4-Ball Test

The TE 92HS Rotary Tribometer was configured as a modified 4-ball machine according to the Institute of Petroleum (UK) IP 300 rolling test procedure. Fig 3 shows the modified 4-ball rolling configuration. The upper ball (3) was held in the collet (2) and rotated at the spindle (1) speed. The retainer cup (7) had a race with slightly bigger radius than a 12.7mm ($\frac{1}{2}$ ") ball to accommodate three lower balls (4). The cup was filled with oil before the test, and during the test period oil could be added through a hole in the cup cover (8) to ensure the test was conducted under fully lubricated condition. A heater pad (5) was connected to a thermocouple to ensure the temperature remained above the specified level. Whenever the temperature falls below this specified level the heater pad will be on.

Four-ball rolling kinematics was described by Kruger and Bartz in Chapter 10 of reference [7]. The current configuration was categorised as a type II machine. The upper ball stress cycle factor L is:

$$L = Z \left[\frac{R_u + 2R_l}{2(R_u + R_l)} \right] \quad (1)$$

Where Z is the number of lower balls, R_u is the upper ball radius, and R_l is the lower ball radius. In this case, $R_u = R_l = 6.35\text{mm}$, $Z=3$. Substitute these figures into equation (1), $L=2.25$. This means that when the spindle rotates one revolution, the upper ball will undergo 2.25 stress cycles.

Before each test, the Si_3N_4 test sample ball and steel balls were cleaned in an ultrasonic bath by acetone. Surface roughness and surface hardness of the sample ball were examined, microscopy inspection was conducted. Lubricant oil was filled to retainer cup before test, and was added every 24 hours during the test to ensure the silicon nitride/steel rolling contact was in a fully lubricated state. The load for 4-ball rolling test is 1.96 kN and speed is 10,000 rpm. In all tests, the temperature setting was 50 °C. Therefore when a new test started, the heater pad was on until the temperature reached 50 °C. The test may be stopped before reaching the set time due to the failure of one of the lower steel balls. In this case the retainer cup assembly is taken out and cleaned. Three new steel balls are then fitted, new oil is added, and the test is continued. The failure of the lower steel ball is normally due to a fatigue spall on the rolling track. By changing the lower steel balls, the rolling contact stress cycles for the upper silicon nitride ball is assured.

2.3 Rolling Contact 5-Ball Test

The 5-ball rolling contact fatigue tester was first reported by Paker and Zaretsky [8] from NASA, USA. In the current study, the 5-ball rolling contact fatigue test was conducted on the TE92 HS Rotary Tribometer, by incorporating a new 5-ball rolling retainer cup designed by the authors. The design of the 5-ball rolling retainer cup made modifications to TE92 HS Rotary Tribometer's 4-ball retainer cup to accommodate four lower balls in the cup instead of three. The race maintained the same radius as the 4-ball cup with a maximum size of 7.62 mm and minimum size of 7.59 mm. The only change was the distance between the two centres of the radius of the race in a section. This measured 13.21 ± 0.02 mm for the 4-ball cup and was increased to 18.20 ± 0.02 mm for the 5-ball cup (Fig. 4). All the other technical specifications and dimensions for the 5-ball cup are the same as for the 4-ball cup in the TE92 HS Rotary Tribometer.

The rolling contact 5-ball test is similar to the 4-ball test described above, except that the retainer cup is a 5-ball cup with four lower steel balls. The upper ball stress cycle factor L can also be calculated from equation (1). In this case, $R_u = R_l = 6.35\text{mm}$, $Z=4$. Substituting these figures into equation (1), $L=3$. It means that when the spindle rotates one revolution, the upper ball will undergo 3 stress cycles. To ensure

that the upper ball undergoes the same stress cycles over the same time interval as in the 4-ball test, the speed of the 5-ball test was set to 7,500 rpm. This means that the upper ball would undergo 22500 stress cycles per minute, the same as in the 4-ball test.

The contact load are also set exactly the same as for the 4-ball test. For the 4-ball test, the load applied by the pneumatic actuator of the Plint machine $P_{machine}$ is 1.96 kN, the contact load $P_{contact4}$ is:

$$P_{contact4} = \frac{P_{machine}}{3\cos(35.3^\circ)} = \frac{1960N}{3\cos(35.3^\circ)} = 800N \quad (2)$$

For the 5-ball test, to maintain the contact load $P_{contact5}$ as 800N

$$P_{contact5} = 800N = \frac{P_{machine}}{4\cos(54.7^\circ)} \quad (3)$$

$$P_{machine} = 800N \times 4\cos(54.7^\circ) = 1.85kN \quad (4)$$

Therefore in the rolling contact 5-ball test, the load was set to 1.85kN, speed was set to 7,500 rpm. All the other settings and the test procedure were exactly the same as for the 4-ball test.

3. Results

3.1 Results of Rolling Contact 4-Ball Test

After running for 136 hours 22 minutes (184 million stress cycles), no failure occurred on upper silicon nitride ball and the surface of the rolling track appeared smoother under optical microscopy (Fig. 5). Occasional surface pitting was also found on the rolling track (Fig. 5 (b)). The characteristic of this sample was many small arc cracks with chord parallel to the rolling direction at the two edges of the rolling track as illustrated in Fig. 5 (b). The chords of these small arc cracks are around 20 μ m, and the shapes and the orientations along the rolling track are the same. The failure of lower steel balls occurred ranging from after 22 hours 37 minutes to after 67 hours with an average failure time 45.5 hours.

Under the same test condition using the same testing steel balls, further 6 silicon nitride ball samples commercially finished or finished by the authors with the surface roughness R_a values ranging from 0.002 to 0.094 μ m were tested for 135-200 million stress cycles. No typical fatigue spalls occurred on any of the silicon nitride samples and the wear on the rolling tracks were also very small. For HIPed silicon nitride balls with a rough surface (0.016 to 0.094 μ m R_a), the surface of the rolling track became smoother due to polishing wear and surface pits in the sizes of 10~20 μ m occurred. For HIPed silicon nitride balls with a

smooth or highly polished surface (0.002 to $0.008 \mu\text{m} R_a$), the surface of the rolling track became rougher and oil residues deposited at the edges of rolling track. Small, shallow surface pitting about $2\mu\text{m}$ in extent also appeared [11].

3.2 Results of Rolling Contact 5-Ball Test

Tests were conducted on four silicon nitride ball samples from the same batch (Table 2). The first ball—No. 1, after running 6 hours and 56 minutes (9.4 million stress cycles), arc cracks (C-cracks, ring cracks) appeared all over the rolling track, more obvious on the outer side half of the track. Fig. 6 (a) and (b) show these arc cracks at different magnifications. The chords of these arc cracks are around $250 \mu\text{m}$, which is nearly half of the rolling track width. After another 5 hours and 1 minute (total 11 hour 57 minutes, 16.1 million stress cycles), this ball failed with a big spall (Fig. 7 (a)). The diameter of this spall is about $500 \mu\text{m}$ and the depth is about $100 \mu\text{m}$ measured by microscopy focus method. It is likely this spall was initiated by two arc cracks in the outer side half of the track, and two arc cracks in the inner side half of the track (upper left), because these arc orientations can be seen inside the spall (Fig. 7 (a)). The arc cracks are now clearly on both sides of the track, prevailing along the entire rolling track (Fig. 7 (b) and (c)). Delamination also occurred on the track (Fig. 7 (c)). It is very interesting that the crack orientations are absolutely opposite at two sides of the track (Fig. 7 (b) and (c)), and this is more clearly illustrated in Fig 8.

To see if this kind of arc cracks is inevitable, No.2 ball was tested for over 135 million stress cycles (102 hours 19 minutes). No arc cracks occurred on the rolling track. After 29 hours and 58 minutes, a symmetric smooth zone appeared on each side of the rolling track (Fig. 9 (a)). The width of this smooth zone is about $170 \mu\text{m}$, which is $1/3$ of the rolling track width. After 53 hours and 51 minutes, it appeared each of the smooth zones was further divided into two portions with an obvious line in the middle. The portions closer to the rolling track centre became even smoother. After 102 hours and 19 minutes, near the inner edge of the rolling track some continuous small pittings occurred (Fig. 10 (a)), and some evenly distributed round pittings also appeared (Fig. 10 (b) and (c)). The diameters of these round pittings are around $50 \mu\text{m}$. It is very interesting that these round pittings are almost exactly evenly spaced.

No. 3 ball was tested for 24 hours, and No. 4 ball for 22 hours 41 minutes respectively. No arc cracks occurred on these two balls (Fig. 11 (a) and (b)). The appearance of these two tracks, however, is very similar to the appearance of No. 2 ball after 29 hours 58 minutes (Fig. 9 (a)). It was anticipated that it is unlikely for the arc cracks to appear on these two balls within a near extended testing period, (because the

arc cracks appeared on No1 ball only after 6 hours 56 minutes) so further test on these two balls was terminated.

The lower steel balls in 5-ball rolling tests failed ranging from 3 hours 57 minutes to 24 hours, with an average failure time 12 hours 31 minutes.

4. Discussion

The arc cracks occurred on No. 1 ball are considered as traction cracks. The word “traction” here means the frictional force in the Hertzian contact ellipse at upper ball and lower ball contact zone, which drives the lower ball to roll and spin. The source of friction may include elastic hysteresis in rolling, sliding in rolling element due to contact geometry, sliding due to deformation of contacting elements and viscous drag of the lubricant on the rolling element, etc. [2]. The lubricant viscosity, film thickness, contacting surface roughness and ball kinematics must be also taken into account. Although the theoretical calculation of the “traction” in 4-ball rolling and 5-ball rolling is possible, it is very intricate and beyond the scope of this paper.

It was generally recognised that in a counterformal contact on a much larger scale (not by a sharp hard indenter), brittle fracture will occur just outside the Hertz contact zone due to tensile stress when the normal load reaches the critical value. If a tangential force is applied to the contact, as in sliding, the critical normal load necessary to initiate fracture is greatly reduced. In experiments with a TiC sphere on a flat of the same material, the critical normal load was reduced by a factor of 10 under sliding condition in air with coefficient of friction $\mu \approx 0.2$ [12]. Under sliding condition, the cracks which form no longer intersect the surface on complete circles, but in a series of arcs initiated from the trailing edge of the contact zone [12]. Corresponding to the opposite traction crack orientations on the two sides of the rolling track in No.1 ball (Fig. 8), it is possible that this is caused by the spinning of lower steel balls around the centre of contact zones. In the Hertz contact zone, pure rolling only occurs at the generatrix of motion, and the sliding to opposite direction at two sides of the contact zone due to spinning of lower steel ball generated the traction cracks (Fig. 12). Although the spinning of lower steel ball also generated opposite sliding direction at the leading side and trailing side of contact zone. As the lower steel ball rolled along the track, on a specific area on the track at one instance it endures the sliding from up to down, and next instance it will endure the sliding from down to up. So the overall effect of the sliding perpendicular to the rolling direction is counterbalanced. Whereas the sliding parallel to the rolling track is a continuous sliding towards the same direction, on the upper side of the track from left to right and on the lower side of the

track from right to the left (Fig. 12). This kind of continuous sliding eventually leads to the opposite traction cracks at two sides of the track. The rolling direction of upper silicon nitride ball is from the left to the right (Fig. 8), which is opposite in direction to the sliding of steel balls on the outer side half of the track (the lower half of the track). This is why the arc cracks occurred more obvious on the outer side of the track in the first instance (Fig. 6).

In the simplified ball kinematics analysis model by Kruger and Bartz [7] (considering balls and cup are rigid bodies, point contact) as shown in Fig. 13, the spinning of lower ball ω_p projected to the axis through lower ball/upper ball contact point will be $\omega_p \cos(90^\circ - \gamma)$. The calculated γ for 4-ball rolling test is 25.2° , and the calculated γ for 5-ball rolling test is 13.3° . The spinning of lower ball projected to the axis through lower ball/upper ball contact point will be $0.425\omega_p$ for the 4-ball rolling test and $0.23\omega_p$ for the 5-ball rolling test. The simplified ball kinematics model could not explain the opposite traction cracks occurred in No. 1 ball. Obviously, the motion of lower balls is much more complicated than the simplified kinematics model.

The precise analysis of 4-ball and 5-ball rolling motion will need to calculate all the forces acted on the lower balls (dynamic analysis) including the traction (tangential force) and the contact deformation. If consider the centrifugal force of lower balls, the lower ball/cup race contact point will be lifted up, and not be on the axis through the centres of lower ball and upper ball. Because the rolling speed was high, the gyroscopic motion of lower balls is also not neglectable. The sliding pattern in the contact zone might be much more complicated than in Fig. 12, and there might be two points in the contact zone as generatrix of motion [2]. Because the rolling speed was high, the skidding between upper ball and lower ball will also occur. It is anticipated that in the 5-ball rolling test the contact deformation and the complex motion of lower balls due to all the forces acted on them, led to the lower balls sliding to opposite directions at two sides of the contact zone thus to cause the opposite traction cracks in No. 1 ball.

In comparison the rolling tracks of upper Si_3N_4 balls after 4-ball rolling test with those after 5-ball rolling tests, it seems that much severe sliding occurred during the 5-ball rolling. The sliding on the rolling tracks in 5-ball tests featured severe polishing wear on the two sides of the tracks (Fig. 9 and Fig. 11), from after 22 hours 41 minutes (30.6 million stress cycles) to after 53 hours 51 minutes (72.7 million stress cycles). The lubrication regime for the 4-ball and 5-ball rolling tests were calculated [13] and listed in Table 3. The λ ratio for the 4-ball rolling tests is 1, which means the lubrication regime will be in the border of partial EHL and boundary lubrication. The λ ratio for the 5-ball rolling tests is 0.827, which means the lubrication regime will be in the boundary lubrication. The lubrication condition for the 4-ball tests was slightly better than the 5-ball tests. But lubrication regime alone could not explain severe polishing wear only occurred on

the two sides of the tracks in 5-ball tests (Fig. 9 and Fig. 11). This severe polishing wear on the two sides of the rolling track has not appeared on another 4-ball rolling tested Si_3N_4 rough surface with R_a 0.094 μm and R_q 0.132 μm (the λ ratio is 0.91, also in boundary lubrication) under the same contact stress for over 197 million stress cycles [11] (Fig.14). It must be the complex motion of lower balls in 5-ball tests led to the sliding at two sides of the contact zone.

The opposite traction cracks that only occurred in No. 1 ball is still a puzzle. The diameters of lower steel balls in No. 1 test were re-measured, and the deviation is only 1-2 μm . The deformation in the contact zones is much higher than this, so the possibility of only one lower steel ball bearing the entire loading is eliminated. If this is caused by initial surface defect, it could not happen on all over the rolling track in opposite direction. The influences from the material and manufacturing parameters are also rare, because all the upper Si_3N_4 balls (one in 4-ball test, and 4 in 5-ball tests) in this investigation were from the same batch lapped by the authors, and were originally from the same batch ball blanks. However, all the Si_3N_4 balls undergone 5-ball test exhibited severe polishing wear on the two sides of the rolling track (Fig. 9 and Fig. 11). The very possible reason for this severe polishing wear on the two sides of the rolling track in 5-ball rolling tests is the sliding of lower steel balls.

Compared with 5-ball rolling tracks, much less sliding occurred on the 4-ball rolling track (Fig. 5) although it has been tested for 136 hours (184 million stress cycles). Regarding to the small arc cracks in Fig. 5 (b), it is possible that these cracks were small Hertzian cracks formed by asperity contacts. These asperities may be formed during the rough lapping process. Further lapping removed some of these asperities, although some remained with their peaks removed. There are many asperities lying within the contact zone, true contact only thus occurring at the tips of these asperities, which are compressed as elastic solids under normal contact conditions and their deformations are explored by the classic Hertz theory [14]. Because the maximum tensile stress on the whole contact zone is located near the track edge, the small arc cracks are generated there with the chords of the arcs perpendicular to the maximum tensile stress direction. This can be considered as a superposition of small asperities Hertz contact on top of Hertz contact on large scale (on the entire contact zone).

5. Summary

Accelerated 4-ball and 5-ball rolling tests were conducted on HIPed Si_3N_4 ball samples with surface roughness value R_a 0.08 μm , which were rolling against standard steel testing balls in fully lubricated condition. The contact load and stress cycles per minute for 4-ball rolling and 5-ball rolling tests were set the same. The rolling tracks of upper Si_3N_4 ball samples after 5-ball rolling tests were very different from

those after 4-ball rolling tests. Experimental results reveal that severe sliding occurred on the two sides near the edges of the rolling tracks of upper Si_3N_4 ball samples after 5-ball rolling tests. In one case, the opposite arc cracks generated all over the rolling track of the Si_3N_4 ball after 9.4 million stress cycles, and this ball failed after only 16 million stress cycles. There is a possibility that opposite arc cracks were caused by the spinning of the lower steel balls, but this spinning could not be explained by simplified ball kinematics model. The motions of the lower steel balls are much more complicated due to the contact deformation and all the forces acted on them. Only if the sliding on the two sides of the track was in opposite direction, the opposite arc cracks could be generated. The fatigue lives of lower steel balls in 5-ball rolling tests were also greatly shortened, from an average 45.5 hours to 12.5 hours. This experimental study suggests that because of the difference in contact angle and contact geometry, the motion of lower balls in a 5-ball rolling test is very different from 4-ball rolling test, and thus leads to very different RCF test results.

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Fig. 12 Spinning of lower steel ball generated the traction cracks

Fig. 13 Simplified kinematics model

Fig. 14 Another rough surface of HIPed Si_3N_4 after 197 million stress cycles RCF test

Diameter	12.699 mm
Density	7789 (kg/m ³)
Surface roughness R _a	0.024 μm
Surface roughness R _q	0.037 μm
Surface Hardness	907 (Vickers Hardness Number, HV10)
Surface Hardness	65.2 HRC-150kgf

Table 1 Measured geometric and material properties of steel test balls

Diameter	12.698 mm
Density	3160 (kg/m ³)
Surface roughness R _a	0.080 μm
Surface roughness R _q	0.118 μm
Surface Hardness	1682 (Vickers Hardness Number, HV10)

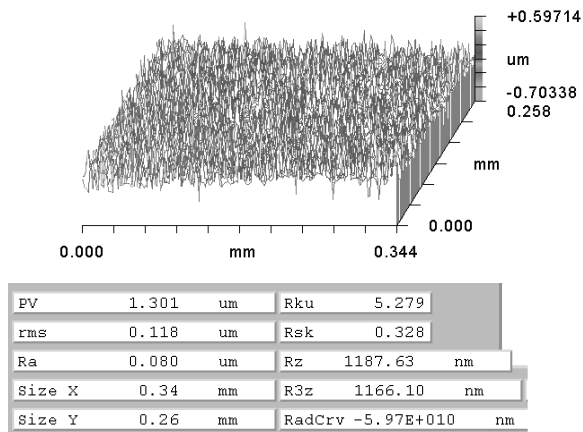
Table 2 Measured geometric and material properties of HIPed Si₃N₄ sample balls

	R _{q1} (μm) ceramic	R _{q2} (μm) steel	h _{min} (μm)	λ
4-ball rolling test	0.118	0.0376	0.125	1.00
5-ball rolling test	0.118	0.0376	0.102	0.827

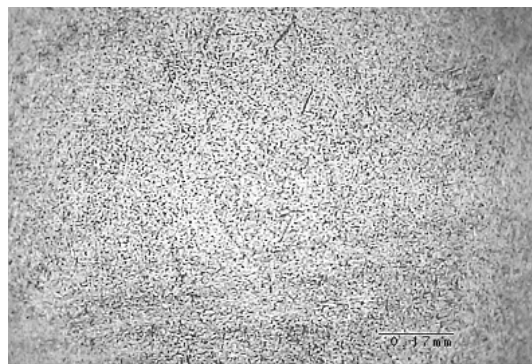
Table 3 The calculated minimum film thickness and lambda ratio for 4-ball and 5-ball tests



Fig. 1 Plint TE 92HS Microprocessor Controlled Rotary Tribometer



(a)



(b)

Fig. 2 3D topographic measurement (a) and microscopy observation (b) of the Si_3N_4 sample ball surface.

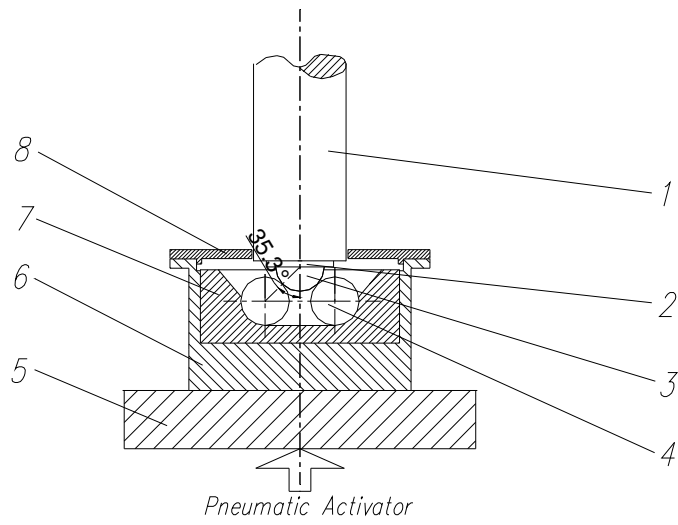


Fig 3 Modified 4-ball rolling configuration

- | | | | | |
|--------------|----------------|--------------|---------------|--------------|
| 1 spindle | 2 collet | 3 upper-ball | 4 lower-balls | 5 heater pad |
| 6 cup holder | 7 retainer cup | 8 cup cover | | |

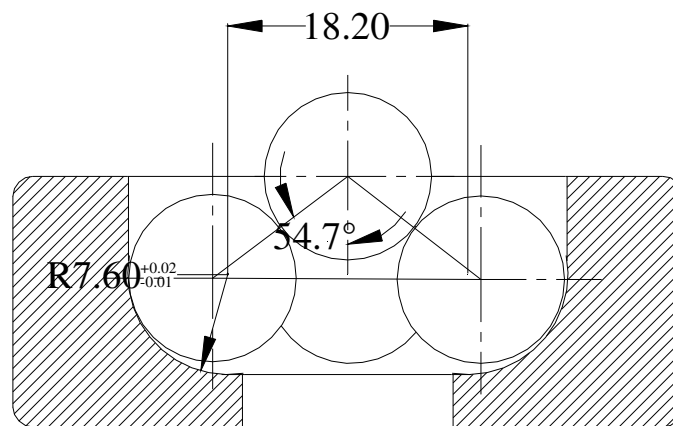
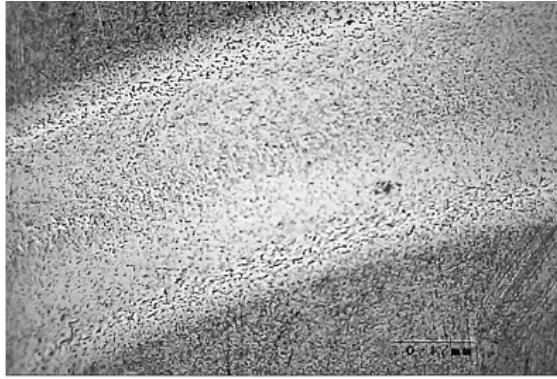
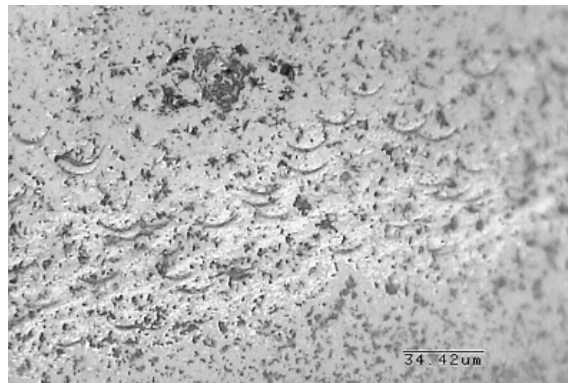


Fig. 4 5-ball rolling cup



(a)

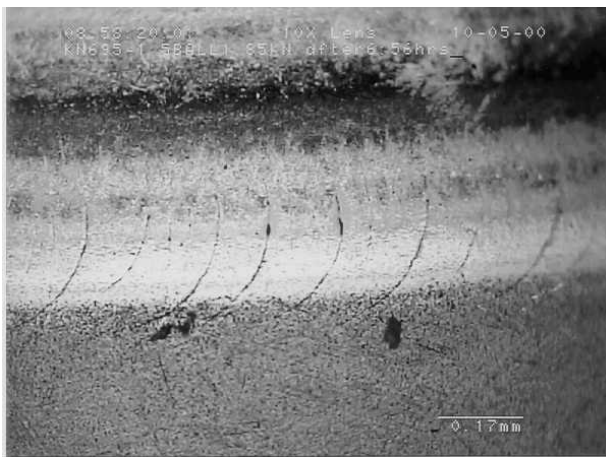


(b)

Fig 5 Rolling track appearance after 136 hours 22 minutes 4-ball rolling test



(a)



(b)

Fig. 6 Arc cracks on No.1 ball after 6 hours and 56 minutes 5-ball rolling test



(a)



(b)



(c)

Fig 7 No.1 ball after 11 hours and 57 minutes 5-ball rolling test

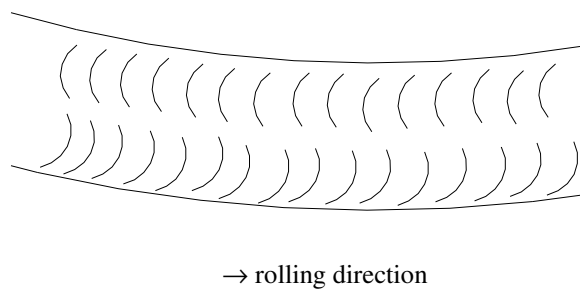
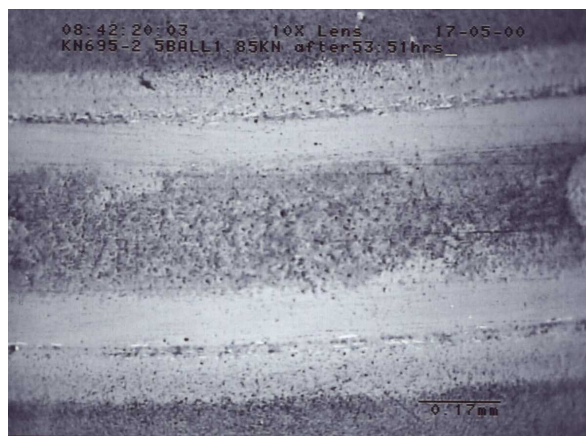


Fig 8 Opposite crack orientations on two sides of the rolling track



(a)



(b)

Fig. 9 No 2 ball after 29 hours 58 minutes (a), and after 53 hours 51 minutes (b) 5-ball rolling test



(a)

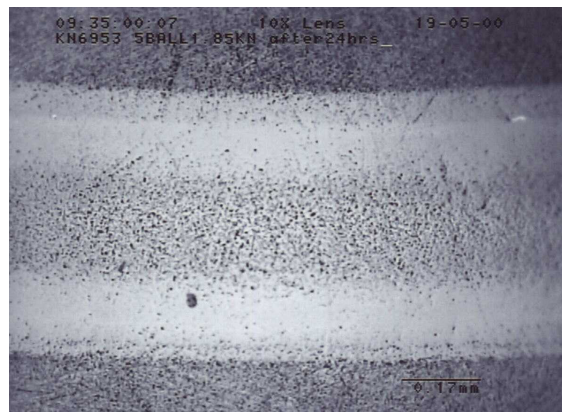


(b)



(c)

Fig. 10 No 2 ball after 102 hours 19 minutes 5-ball rolling test



(a)



(b)

Fig 11 No. 3 ball after 24 hours (a), and No. 4 ball after 22 hours 41 minutes (b) 5 ball rolling test

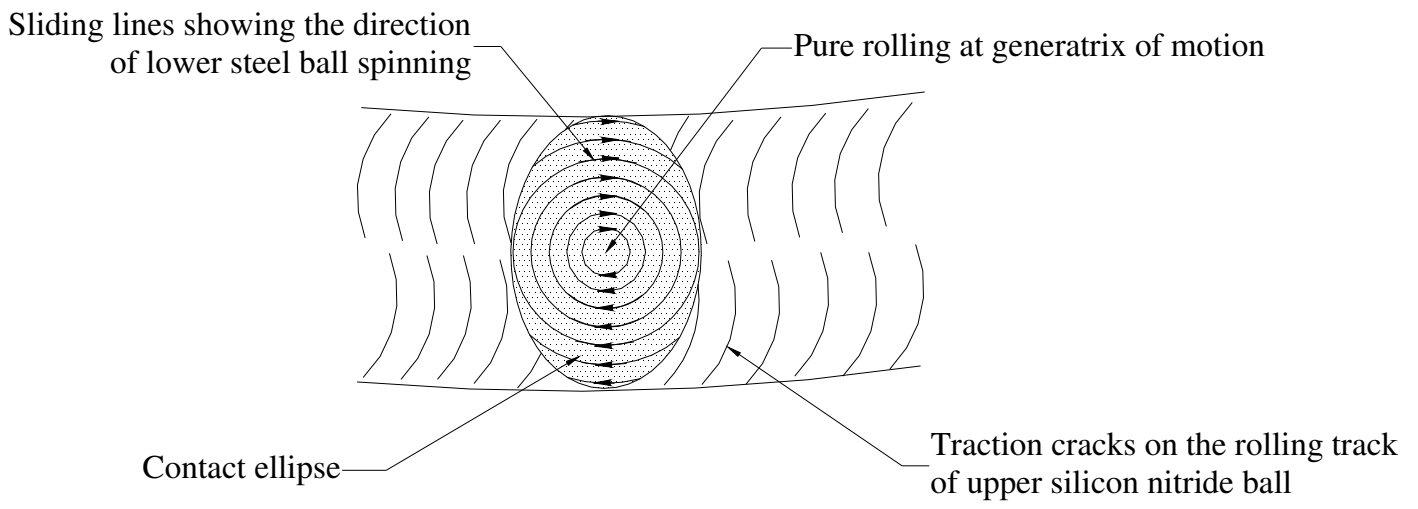


Fig. 12 Spinning of lower steel ball generated the traction cracks

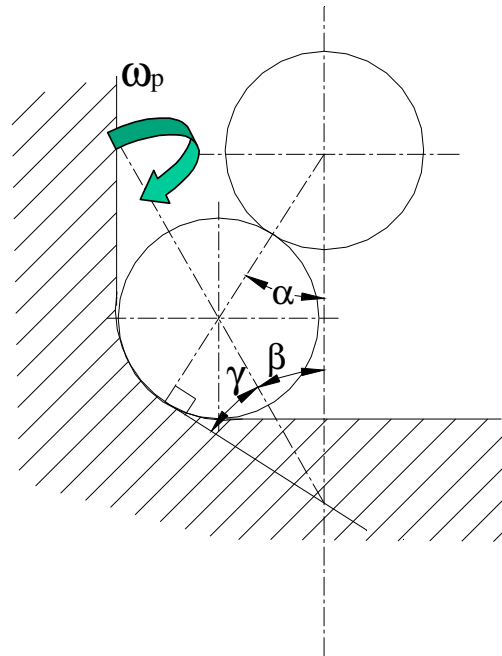


Fig. 13 Simplified kinematics model

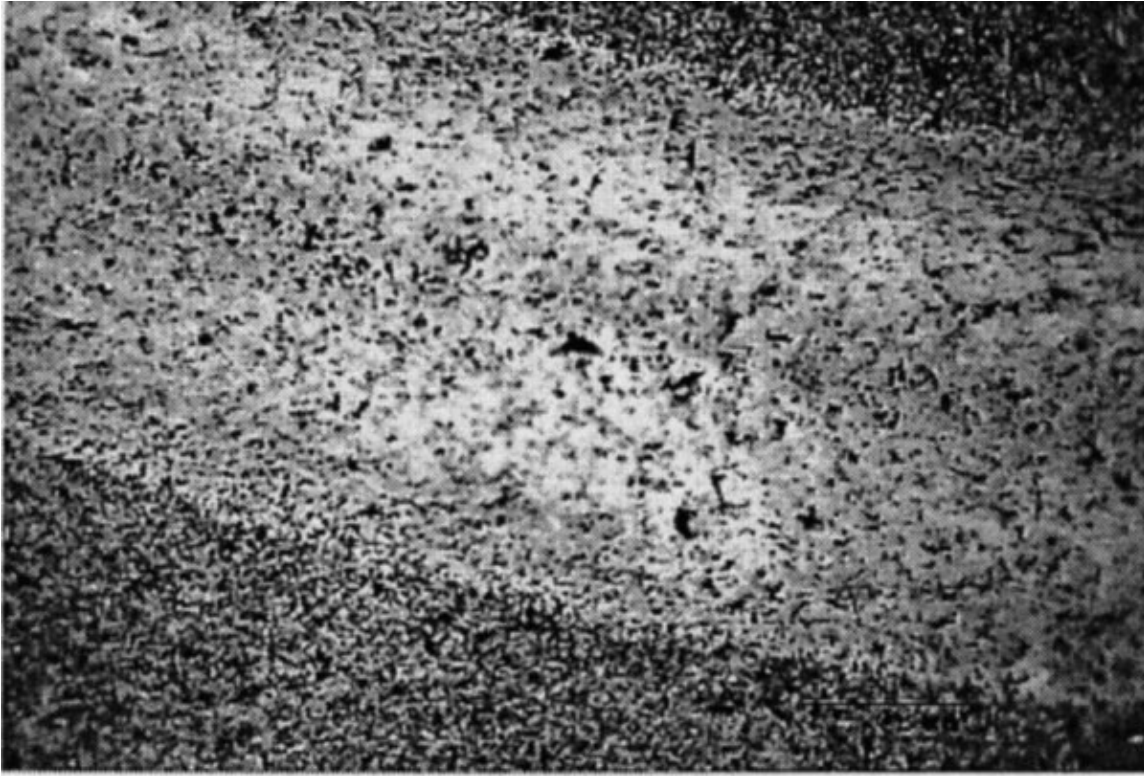


Fig. 14 Another rough surface of HIPed Si_3N_4 after 197 million stress cycles RCF test