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# Experimental Study on Friction and Wear Behaviors of Ball Bearings under Gas Lubricated Conditions

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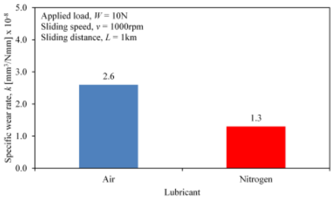
**Graphical abstract**



## Abstract

Friction and wear behaviors of ball bearings made from carbon-chrome steel were experimentally simulated using a modified ball-on-disc tribometer. The test was performed over a broad range of applied loads (*W*), sliding velocities (*v*) and sliding distances (*L*) under gas lubricated conditions using a Taguchi method. The results found that gas blown to the sliding surfaces in air effectively reduced the coefficient of friction as compared with the air lubrication at higher applied load, sliding speed and sliding distance. In addition, a specific wear rate is constant throughout the tests under gas lubricated conditions. However, under air lubrication, the specific wear rate decreases with increasing applied load, sliding speed and sliding distance. By using the optimal design parameters, a confirmation test successfully verify the $N_2$-gas lubrication reduced average coefficient of friction and simultaneously improved wear resistance about 24% and 50%, respectively. This is in accordance with a significant reduction of wear scar diameter and smoother worn surface on a ball.

*Keywords*: Coefficient of friction; wear rate; gas lubrication; Taguchi method

## Abstrak

Sifat geseran dan kehausan pada galas yang dibuat daripada keluli karbon-krom telah uji menggunakan tribometer bola-ke-cakera yang diubahsuai. Ujian dijalankan dengan pelbagai beban (W), halaju (v) dan jarak (L) di bawah peliciran gas dengan menggunakan kaedah Taguchi. Dapatan ekperimen menunjukkan tiupan gas yang dilepaskan pada permukaan gelongsor dapat mengurangkan nilai pekali geseran berbanding pelinciran udara pada beban, kelajuan dan jarak yang lebihan. Walau bagaimanapun, di bawah pelinciran udara, kadar kehausan berkurangan dengan peningkatan beban, halaju dan jarak yang dikenakan. Dengan menggunakan reka bentuk parameter optimum, satu pengesahan ujian telah mengesahkan pelinciran $N_2$-gas mengurangkan pekali geseran dan kehausan dapat diperbaiki pada 24% dan 50%. Ini adalah selaras dengan pengurangan saiz diameter kehausan dan permukaan yang elok pada bebola galas.

*Kata kunci*: Pekali geseran; kadar kehausan; pelinciran gas; kaedah Taguchi

## ■1.0 INTRODUCTION

Ball bearings are small metal balls that are used in a wide variety of machines and other devices, allowing parts of them to spin freely and without friction. However, these ball bearings will sometimes run into problems due to overuse, extreme vibrations or improper upkeep [1]. Besides, the bearing lubricants such as grease must be replaced periodically and if bearing gets too warm, grease melts and runs out of bearing.

Nowadays, there are a great variety of advanced lubrication technologies includes thin film coatings [2-5], nanolubricants [6-7] and gas lubricants [8-11]. However, gas lubrication is the most cost effective and has several advantages, such as high precision, small friction loss, non–polluting, vibration-free, long life and attractive for high-temperature applications [12].

Cong *et al*. [8] found that HFC-134a gas significantly reduces the friction and wear of all the ceramic couples (ionic ceramics $Al_2O_3$ and $ZrO_2$, and the covalent ceramics $Si_3N_4$ and SiC rubbing against an $Al_2O_3$ ball), and that the ionic ceramic pairs show lower friction and wear. Oxygen has been found to lubricate SiC by the formation of silica and the release of graphite-like material [9], while benzene and acetone vapors have been found to form sticky reaction products, which reduce the friction and wear of $ZrO_2$ [10].

From the past researches, friction and wear of materials are effectively reduced by different gas lubrications. However, researches on this topic are not much explored. Thus, in this study, the friction and wear behaviors of ball bearings made from carbon-chrome steel, sliding in air with $O_2$- or $N_2$-gas blows, are investigated using a systematic approach, which is Taguchi method. Additionally, the optimal design parameters are obtained by employing analysis of signal-to-noise ($SN$) ratio. Then, a confirmation test was carried out to verify the improvement of the quality characteristic using optimal levels of the design parameters.

## 2.0 EXPERIMENTAL PROCEDURES

### 2.1 Design of Experiment (DoE)

Prior to experimental work, design of experiment (DoE) using Taguchi method was employed. Four design parameters were determined (lubricant, applied load, sliding speed and sliding distance) and three levels were taken for each parameter, as shown in Table 1. In this study, the $L_9$ ($3^4$) orthogonal arrays was selected using Minitab statistical software, as shown in Table 2.

**Table 1** Design parameters at three different levels

| Level | Design parameters | | | |
|---|---|---|---|---|
| | **Lubricant** | **Applied load ($W$), N** | **Sliding speed ($v$), rpm** | **Sliding distance ($L$), km** |
| 1 | Air | 5 | 50 | 1 |
| 2 | $N_2$-gas | 10 | 1000 | 3 |
| 3 | $O_2$-gas | 20 | 1500 | 5 |

**Table 2** Taguchi $L_9$ ($3^4$) orthogonal arrays

| Test | Design parameters | | | |
|---|---|---|---|---|
| | **Lubricant** | **Applied load ($W$), N** | **Sliding speed ($v$), rpm** | **Sliding distance ($L$), km** |
| 1 | Air | 5 | 500 | 1 |
| 2 | Air | 10 | 1000 | 3 |
| 3 | Air | 20 | 1500 | 5 |
| 4 | $N_2$-gas | 5 | 500 | 5 |
| 5 | $N_2$-gas | 10 | 1000 | 1 |
| 6 | $N_2$-gas | 20 | 1500 | 3 |
| 7 | $O_2$-gas | 5 | 500 | 3 |
| 8 | $O_2$-gas | 10 | 1000 | 5 |
| 9 | $O_2$-gas | 20 | 1500 | 1 |

### 2.2 Materials

The materials used in this study were carbon-chrome steel (SKF ball bearing) for a ball and EN-31 steel for a disc. The ball has an average surface roughness ($R_a$) of 0.023 µm. The mechanical properties of materials are shown in Table 3.

**Table 3** Mechanical properties of materials

| Properties | Carbon chromium steel[a] | EN-31 [b] |
|---|---|---|
| Hardness ($H$), HRC | 61 | 65 |
| Density ($\rho$), g/cm$^3$ | 7.79 | 7.81 |

[a] From laboratory measurements.
[b] From manufacturer.

### 2.3 Tribological Testing

By selecting $L_9$ Taguchi's orthogonal arrays as in Table 2, nine simulated sliding tests were carried out using a modified ball-on-disc tribometer in accordance with ASTM standard G99-95a [13], as illustrated in Figure 1. Each test was repeated two times in order to reduce experimental errors. Gas was blown to the sliding surfaces in air at a constant pressure of 10 psi (70 kPa), as shown in Figure 2. All tests were performed at room temperature and in a closed chamber in order to trap and minimize the gas leakage to the atmosphere. Prior to the sliding test, both ball and disc were cleaned using acetone in an ultrasonic bath. The ball and disc has a diameter of 11 mm and 165 mm (thickness of 8 mm), respectively.

A coefficient of friction and frictional force encounter by the ball in sliding were measured by a PC based data logging system. The coefficient of friction is then being determined as follows:

$$\mu = F/W \qquad (1)$$

where $F$ is the frictional force in N and $W$ is the applied load in N.

The wear at the ball was recorded by measuring the mass of the ball before and after the wear test. The mass loss in mass unit is converted to the volume loss by dividing with bulk density of material. The specific wear rate is then being determined as follows:

$$V_{loss} = m_{loss}/\rho \quad (2)$$

$$k = V_{loss}/WL \quad (3)$$

where $V_{loss}$ is the volume loss in $mm^3$, $m_{loss}$ is the mass loss in g, $\rho$ is the bulk density of material in $g/mm^3$, $k$ is the specific wear rate of material in $mm^3/Nmm$, $W$ is the applied load in N and $L$ is the sliding distance in mm.

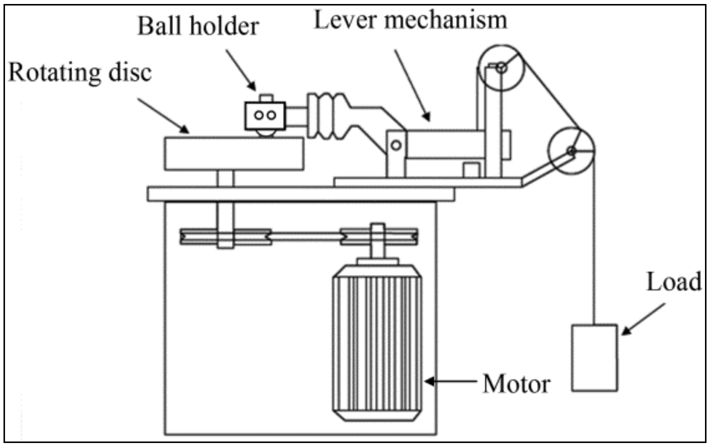


**Figure 1** Schematic diagram of a ball-on-disc tribometer

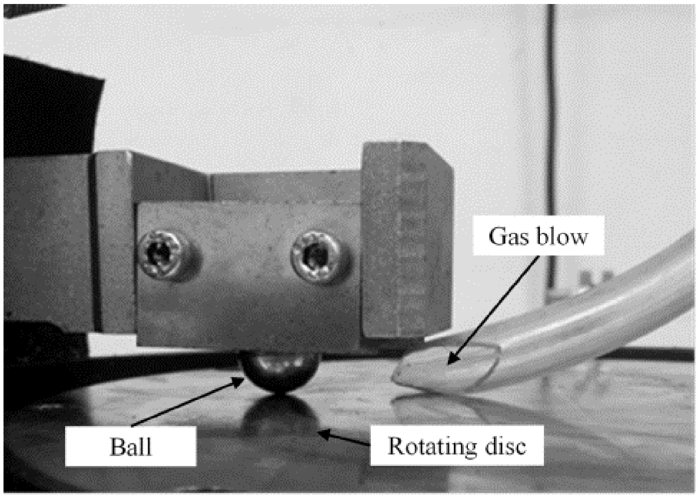


**Figure 2** Photograph of a modified ball-on-disc tribometer with gas blown to the sliding surfaces

## ■3.0 RESULTS AND DISCUSSION

### 3.1 Effect of Gas Lubrication on Friction and Wear Behaviors of Ball Bearings

Generally, two surfaces of adjacent moving parts can be separated by a thin film to minimize direct contact between them and provides an interface of low shear strength, hence reduce friction and wear. In this study, the presence of gas lubrication potentially created a thin film and lowered the coefficient of friction at higher applied load, sliding speed and sliding distance as compared with the air lubrication, as shown in Figure 3. This may be due to the shear strength increases less in proportion to the applied load, sliding speed and sliding distance; this leads to a slight reduction of friction.

From Figure 4, a specific wear rate is constant throughout the tests under gas lubricated conditions. On the other hand, under air lubrication, the specific wear rate decreases significantly with increasing applied load, sliding speed and sliding distance. With further increase in load, speed and distance; frictional heating may occur due to the interaction of the asperities of two contact surfaces and in this case the wear process may consist of formation and removal of oxide on the surface, as shown in Figure 5, resulting in reduction of wear rate.

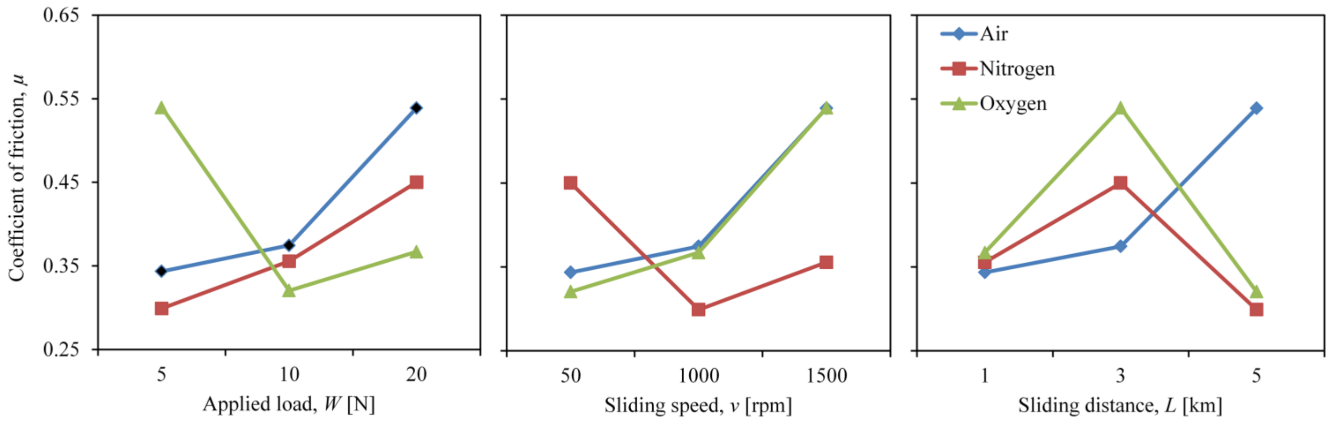


**Figure 3** Interaction plot for coefficient of friction

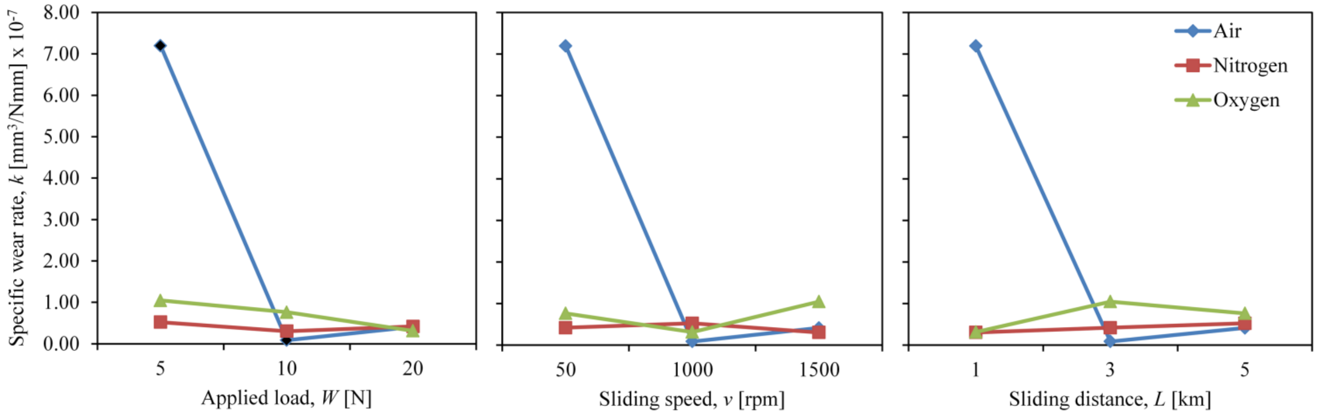


**Figure 4** Interaction plot for specific wear rate

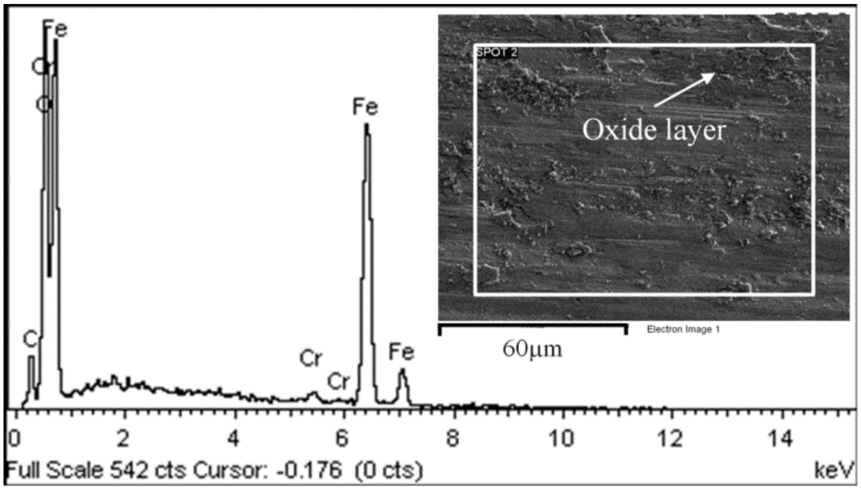


**Figure 5** EDX spectrum at the worn surface of a ball

## 3.2 Optimal Design Parameters

According to Taguchi method studies, response variation using the signal-to-noise (*SN*) ratio is important, because it can result in the minimization of quality characteristic variation, due to uncontrollable parameters. The coefficient of friction was considered as being the quality characteristic, using the concept of the "smaller-the-better". The *SN* ratio used for this type of response was given by:

$$SN = -10\log_{10}\left(\sum \frac{y^2}{n}\right) \tag{4}$$

where, *n* is the number of measurement values in a test, in this case, *n* = 2, and *y* is the measured value in the test. *SN* ratio values are calculated by taking into consideration EqUATION 4.

The coefficient of friction values measured from the test, and their corresponding *SN* ratio values, are shown in Figure 6. A greater *SN* ratio value corresponds to a better performance (lower coefficient of friction). Based on Figure 6 and the rank of mean of *SN* ratio as shown in Table 4, all design parameters have a significant effect on the coefficient of friction. Although, the sliding speed (rank 1) is the most influencing factors for minimizing coefficient of friction, a small increase in a mean of *SN* ratio indicating that the presence of $N_2$-gas lubrication effectively reduced coefficient of friction. In this study, the optimal design parameters for a lower coefficient of friction are identified as follows: lubricant = $N_2$, *W* = 10 N, *v* = 1000 rpm, *L* = 1 km.

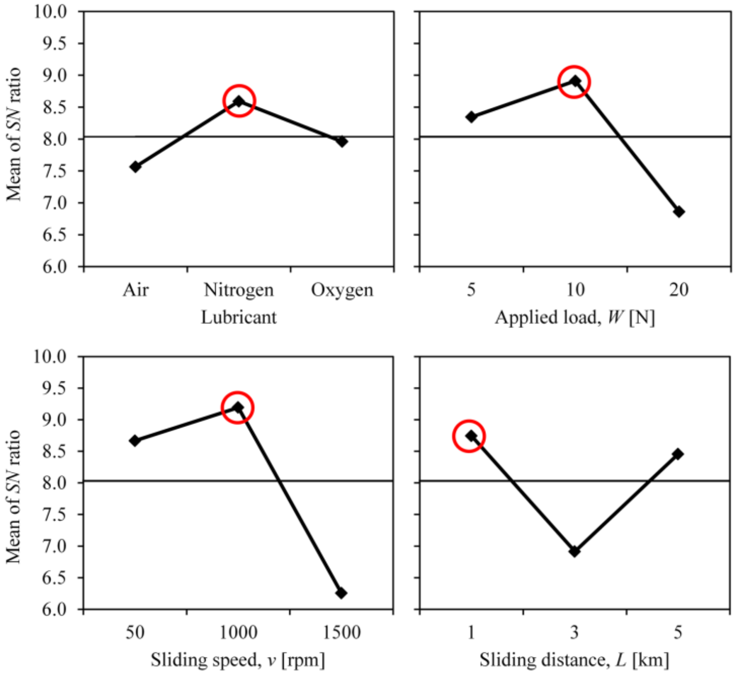


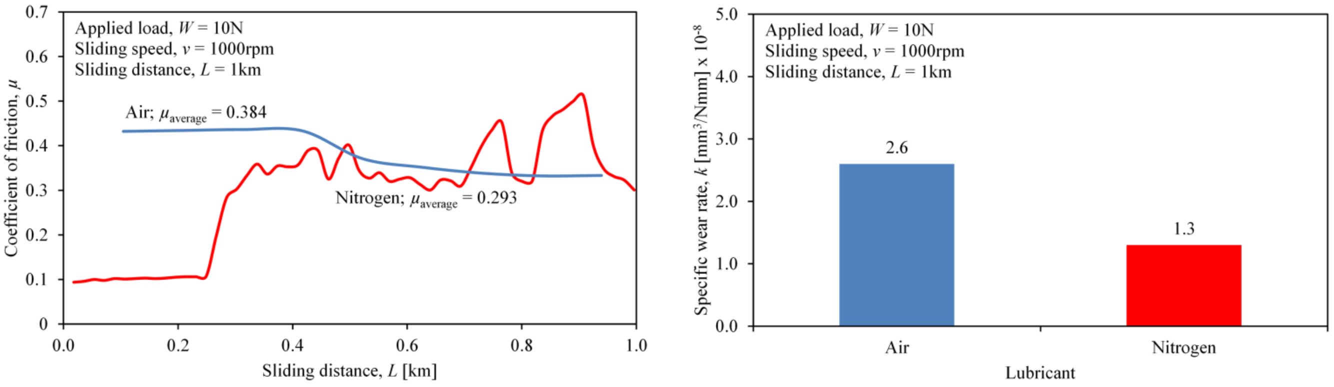
**Figure 6** Mean of SN ratio for coefficient of friction. The optimal parameter is shown by a red circle

**Table 4** Response table of *SN* ratios for coefficient of friction

| Level | Design parameters | | | |
|---|---|---|---|---|
| | **Lubricant** | **Applied load (*W*), N** | **Sliding speed (*v*), rpm** | **Sliding distance (*L*), km** |
| 1 | 7.564 | 8.345 | 8.667 | 8.745 |
| 2 | 8.591 | 8.911 | 9.193 | 6.914 |
| 3 | 7.959 | 6.859 | 6.254 | 8.456 |
| Delta | 1.027 | 2.052 | 2.939 | 1.831 |
| Rank | 4 | 2 | 1 | 3 |

## 3.3 Confirmation Test

A comparison between the optimized values in air and $N_2$-gas lubrication is shown in Figure 7. A confirmation test can successfully verify the $N_2$-gas lubrication reduced average coefficient of friction and simultaneously improved wear resistance about 24% and 50%, respectively. This is in accordance with a significant reduction of wear scar diameter on a ball, as shown in Figure 8. Furthermore, Figure 9 shows that a smoother worn surface ($R_a$ = 0.162 μm) was also obtained under $N_2$-gas lubricated conditions.



(a) (b)

**Figure 7** A confirmation test results by comparing (a) the coefficient of friction and (b) specific wear rate of a material under air and $N_2$-gas lubricated conditions using optimal design parameters

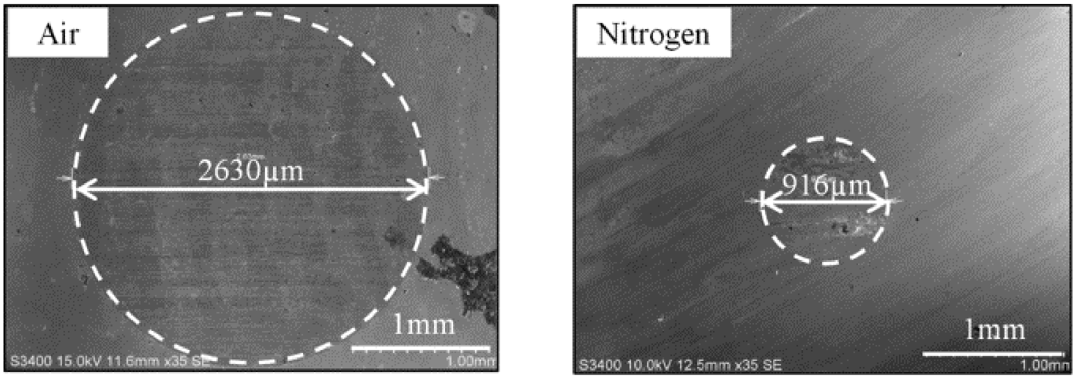


**Figure 8** Scanning Electron Microscopy (SEM) of worn surfaces on the balls under air and $N_2$-gas lubricated conditions using optimal design parameters

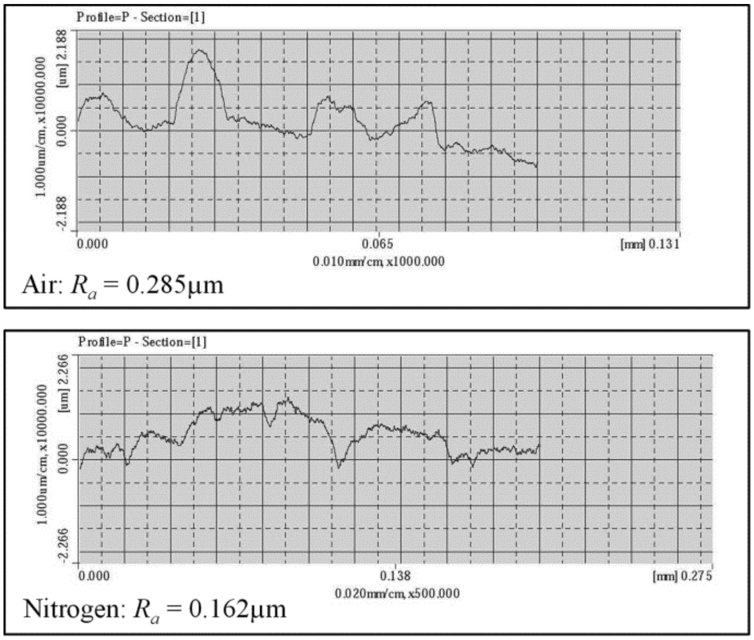


**Figure 9** Surface profile of worn surfaces on the balls under air and $N_2$-gas lubricated conditions using optimal design parameters

## ■4.0 CONCLUSION

The following conclusions may be drawn from the present study:

a) As compared with the air lubrication, the presence of gas lubrication lowered the coefficient of friction at higher normal load, sliding speed and sliding distance. This may be due to the shear strength increases less in proportion to the applied load, sliding speed and sliding distance.

b) A specific wear rate is constant throughout the tests under gas lubricated conditions. On the other hand, under air lubrication, the specific wear rate decreases with increasing applied load, sliding speed and sliding distance. With further increase in load, speed and distance; frictional heating may occur and wear process may consist of formation and removal of oxide on the surface, resulting in reduction of wear rate.

c) The optimal design parameters for a lower coefficient of friction are: lubricant = $N_2$, $W = 10$ N, $v = 1000$ rpm, $L = 1$ km.

d) By using the optimal design parameters, a confirmation test successfully verify the $N_2$-gas lubrication reduced average coefficient of friction and simultaneously improved wear resistance about 24% and 50%, respectively. This is in accordance with a significant reduction of wear scar diameter and smoother worn surface on a ball.

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