Performance studies of textured race ball bearing

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Abstract

Purpose – The purpose of this paper is to develop an energy-efficient and dynamically improved thrust ball bearing using textured race. A texture has been used on the stationary race of the test bearing to conduct the long-duration experiment for exploring its tribological and vibrational behaviours under starved lubricating condition using micro size MoS2 blended grease. The performance behaviours of the textured race bearing have been compared with conventional bearing (i.e. having both races without textures) under the identical operating conditions for demonstrating the advantages of textured race.

Design/methodology/approach – Texture was created on stationary race of the test ball bearing (51308) using nano-second pulsed Nd: YAG laser. Performance parameters (frictional torque, temperature rise and vibrations) of textured ball bearings were measured under severe starved lubricating conditions for understanding the critical role of texture in the long duration of the test. S-type load cell and miniature accelerometer were used for measuring the frictional torque and vibration, respectively. Bulk temperature at stationary races (at the back side) of test bearings was measured in operating conditions using a non-contact infrared thermometer.

Findings – Significant reduction in frictional torque and decrease in amplitude of vibration with textured ball bearing were found even under the severe starved lubricating condition in comparison to conventional bearing.

Originality/value – There is dearth of research pertaining to the performance behaviours of ball bearings using textures on the races. Therefore, an attempt has been made in this study to explore the tribo-dynamic performance behaviours of a thrust ball bearing using a texture on its stationary race under severe starved lubricating condition for the longer duration of the test.

Keywords Vibrations, Ball bearing, Frictional torque, Starved lubrication, Textured race

Paper type Research paper

1. Introduction

Rolling bearings are widely used in industrial and domestic machines for supporting and guiding the loaded rotors energy-efficiently. These bearings possess inherent low damping capacity due to ineffective lubrication because of poor lubricant retainability at the concentrated contacts. In rolling bearings, simultaneously pushing aside of lubricants from the tracks (due to the continuous motion of rolling elements) and its throwing away (in presence of centrifugal action) create the starved lubricating condition (Wikstrom and Jacobson, 1997; Larson and Lugt, 2008; Bhardwaj *et al.*, 2017). Figure 1 illustrates the removal of grease from a ball's track. Similar thing happens in the ball bearings when many balls move fast on the track under the loaded condition. This yields starved lubrication at the ball/race contacts. This deteriorates the bearing performances (Damiens *et al.*, 2004; Nogi *et al.*, 2018). Thus, increasing the lubricant's retainability at the balls' track is a vital task for reducing the friction and vibration of ball bearings.

The roles of textures on the performance behaviours of different generic concentrated contacts have been explored by many researchers (Sudeep *et al.*, 2015a; Gropper *et al.*, 2016; Houdková *et al.*, 2017; Gachot *et al.*, 2017; Grützmacher *et al.*, 2018). The frictional (Gualtieri *et al.*, 2009; Kovalchenko *et al.*, 2011; Podgornik *et al.*, 2012; Rosenkranz *et al.*, 2015; Sudeep *et al.*, 2013, 2015b, 2016a, Tripathi *et al.*, 2016; Wos *et al.*, 2015; Yu *et al.*, 2013), wear (Kovalchenko *et al.*, 2011; Sudeep *et al.*, 2015b, 2016a; Tripathi *et al.*, 2016; Rosenkranz *et al.*, 2016) and vibration (Sudeep *et al.*, 2013, 2016a, 2016b) performances of textured contacts have been studied fairly in-

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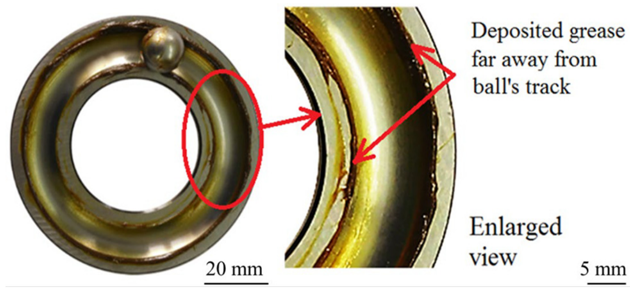
Figure 1 Pictorial illustration of pushing aside of grease and its deposition far away from the track because of movement of a ball



depth. Based on these studies, reductions in friction and vibration have been found in the range of 23-50 per cent and 14 per cent-38 per cent, respectively. Approximately 50 per cent increase in the minimum film thickness at the lubricated textured point contact is reported (Hirayama *et al.*, 2014). It is also reported that the micro-dimples (or micro-features) of texture created by the nano/femto second pulsed Nd: YAG lasers exhibit micro-cutting of the counter surface at the contacts. This enhances the contact area, which results in the shifting of lubrication regime from boundary to mixed and consequently yielding reductions in friction and vibration (Gualtieri *et al.*, 2009; Kovalchenko *et al.*, 2011; Sudeep *et al.*, 2015b). It has been established that the texture attributes (size, pitch, depth, area density of dimples etc.) play vital role on the tribological and vibration behaviours of textured concentrated contacts.

Based on the literature review (Sudeep *et al.*, 2015a; Gachot *et al.*, 2017), it is noticed that many researchers have reported their findings mainly for the generic textured concentrated contacts. It is seen that the correlation of their findings with the mechanical systems/elements involving the textured concentrated contacts could not be found. The authors did not observe the explorations on the tribo-dynamic performances of rolling bearings using the textures in the literature in spite of encouraging results achieved and reported with generic textured contacts. Thus, the objective of this study is set to use the textured race in test ball bearing (51308) for understanding the critical role of texture on the bearings' frictional torque, vibrational behaviours and temperature rise. Conventional and textured race test bearings were operated for long duration (corresponds to 2.24 million revolutions) under the severe starved lubricating conditions (using micro size MoS_2 blended grease) to compare the performance parameters. Moreover, the performance parameters of conventional and textured race test bearings run in dry conditions (without use of any lubricant) have also been provided and discussed.

2. Experimental description

Textures comprising of dimples (diameter = 92 – 110 μm, depth = 30 μm, circumferential/radial pitch = 360 μm, dimple area density = 11 per cent) were created on stationary race of commercially available thrust ball bearing (51308) using nano-second pulsed Nd: YAG laser (wavelength = 1064 nm, frequency = 25 kHz, power = 18 W, speed = 0.3 m/s, pulse duration = 50 ns, laser fluency = 83 J/cm^2 per pulse). It is worth noting here that based on the experimental investigations reported by the researchers (Sudeep *et al.*, 2013, 2015a, 2015b; Podgornik *et al.*, 2012; Kovalchenko *et al.*, 2011; Tripathi *et al.*, 2016), it was understood that dimples' diameter must be much lesser than the Hertzian width for achieving good results. In the present investigation two loads [90N (pH = 0.4 GPa), 300 N (pH = 0.6 GPa)] were used for investigating the roles of textured race on the bearing's performances. The Hertzian widths (along minor axis) at loads 90 N and 300 N were computed 92 μm and 136 μm, respectively. Thus, intention was to create dimples of diameter lesser than 92 μm in the texture, but because of the manufacturing constraint associated in laser texturing on the curved race, the quality dimples with less than 100 μm dimensions could not be achieved. Thus, it was decided to keep dimples of dimeter in such a way, which can be fabricated properly. This led dimples' diameters varying in the range of 92-110 μm. Commercially available lithium soap based general purpose grease (SKF LGMT3) blended with MoS_2 (3 per cent by weight) was used as lubricant in this investigation. The percentage weight of MoS_2 was arrived based on the experiments conducted using four ball tester. The morphology of MoS_2 was flakes type with average thickness 200 nm and other dimensions around 2-3 μm. The properties of lubricating grease are listed in Table I.

The photographic view of a textured race has been shown in Figure 2(a). The CAD model of test setup used is also shown Figure 2(b). Lower race of test bearing is coupled with rotating shaft, while the upper race is held stationary. Frictional torque is measured using a torque arm and S-type load cell as illustrated in Figure 2(c). Bulk temperature at stationary race (at the back side) was measured in bearings' operating conditions using a non-contact infrared thermometer. For assessing the retainability and distribution of grease on the moving races of conventional and textured test bearings, the thermographs of races were captured in stationary condition by dismantling the race holders [refer to Figure 2(d) for view of holders] within less than a minute's time after end of the experiments i.e. on completion of 2.24 million revolutions. For this purpose, a high resolution infrared camera (Model-FLIR P640) possessing the operating details listed in the Table II was used.

The vibration spectra of test bearings in the direction of loading have been picked-up using a piezoelectric

Table I Properties of lubricating grease blended with MoS_2

Soap type	Lithium
Base oil	Mineral oil
Viscosity of base oil at 40°C (mm^2/s)	125
Viscosity of base oil at 100°C (mm^2/s)	12
Apparent viscosity of base grease, Pa-*s* (@ 30° C and 100 s^{-1} strain rate)	11.30
NLGI number	3
Worked penetration (60 St, 10^{-1} mm)	245
Operating temperature range (°C)	−30 to 120
Drop point (°C)	>180

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Figure 2 (a) Photographic view of stationary textured race; (b) CAD model of experimental setup; (c) load cell and arm arrangement for frictional torque measurement; (d) view of race holders and mounted accelerometer on stationary race holder

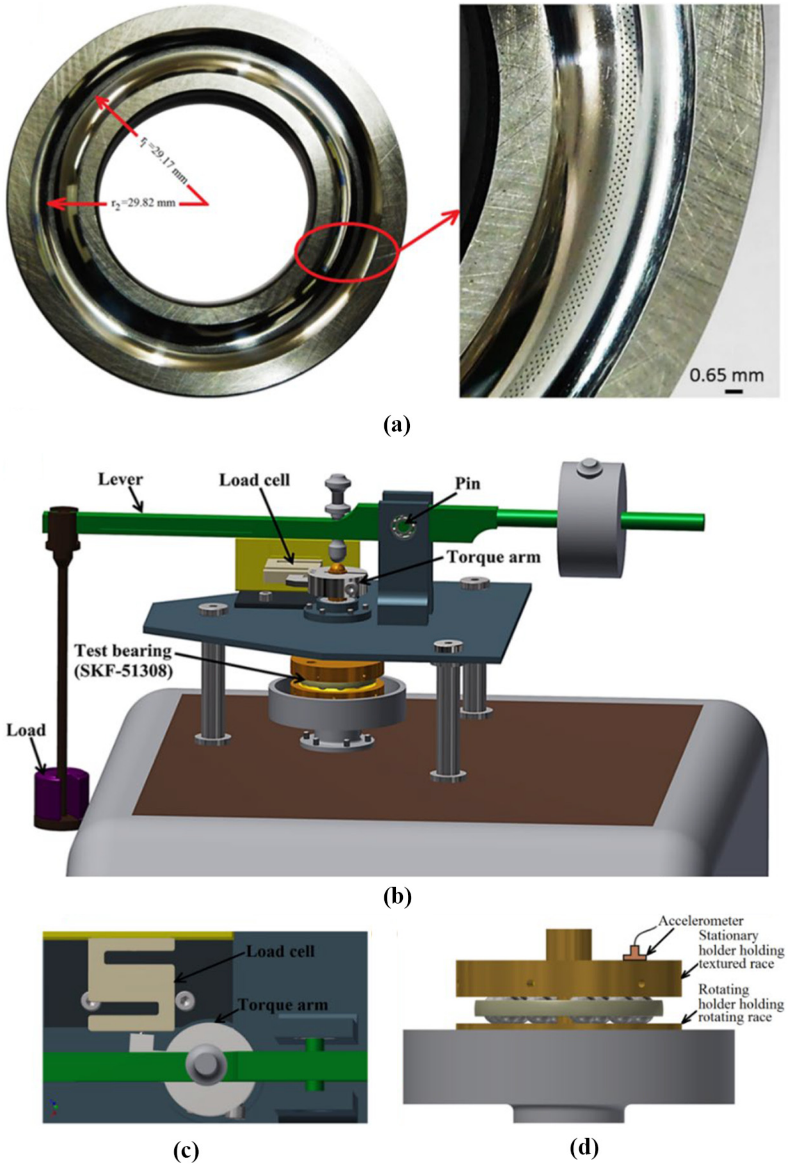


Table II Technical specifications of the infrared camera

Measurement	
Thermal sensitivity	0.06° C @ 30° C
Accuracy (% of reading)	± 2% of the reading
Temperature ranges	−40°C to 500°C
Focus	Automatic or manual
Measurement features	Automatic corrections based on user input
Environment	
Operating temp range	−15°C to 50°C
Humidity	10%-95%

accelerometer (B & K type 4366) at stationary race [refer to Figure 2(d)]. All the experiments reported herein were conducted at the ambient condition [room temperature = 26°C ± 2°C, relative humidity = 50-60 per cent] at two loads 90 N (p_H = 0.4GPa) and 300 N (p_H = 0.6 GPa) and velocities varying in the range of 2-4 m/s using fresh and MoS_2 blended greases. Keeping in mind the guidelines provided by the manufacturers of rolling bearings, the quantity of grease was decided for creating the starved lubrication. At each load and speed, experiments were conducted in two time slots each having 1.12 million revolutions. After first 1.12 million revolutions, experiments on test bearings were stopped for a day. Thereafter, test bearings were operated again for 1.12 million revolutions (cumulative 2.24 million revolutions) for checking the repeatability of results. During the experiment at the time interval of every 60 min, the frictional torque, temperature rise and vibration of test bearings were recorded.

3. Results and discussions

3.1 Performance behaviours of grease lubricated bearings

Figures 3(a)-(f) show variations of frictional torque, bulk temperature rise, and vibrations (in time and frequency domain) of grease lubricated conventional and textured ball bearings for 2.24 million revolutions of rotating race. It can be observed in Figure 3(a) that towards the ending of 2.24 million revolutions, the textured bearing yields about 19 per cent reduction in the frictional torque in comparison to the conventional bearing. In Figure 3(a), a dip in the frictional torque values can be seen at 1.12 million revolutions. This happens because of the stopping and re-start of the experiments at this point. Experiments were conducted in two time slots each having 1.12 million revolutions. After first 1.12 million revolutions, experiments were stopped for 24 h. Thereafter, test bearings were operated again for 1.12 million revolutions (cumulative 2.24 million revolutions) for checking the repeatability of the results. About 14 per cent decrease in bulk temperature rise at the stationary race of textured bearing is recorded in comparison to conventional bearing, which can be seen in Figure 3(b). It is established through the evidences shown in the figures to appear that reductions in frictional torque and temperature rise with textured bearing happen because of the better retainability of the grease at the contacts of races/balls. The vibrations with conventional and textured bearings (towards ending of 2.24 million revolutions) are shown in Figs. 3(c)-(f) in time and frequency domains. Textured race bearing has yielded substantial reduction in vibrations in both time and frequency domains in comparison to conventional bearing. In frequency domain, the amplitudes of vibration at rotational frequency (and at their harmonics) are substantially less in case of textured race bearing than conventional bearing. Textured bearing exhibits about 21 per cent reduction in vibration amplitude at the rotational frequency. This also happens because of the improvement in the retainability of lubricant at the interfaces of balls and races in presence of texture. This enhances the damping at the balls/races contacts leading to reduction in vibrations. The mechanisms leading to the improvement in the performance behaviours of textured bearing and related evidences have been presented in the paragraphs and figures to come.

In the presence of texture and MoS_2 blended grease in bearing, the balls/races contacts may experience four situations as schematically illustrated in Figure 4(a)-(d). These situations mainly depend on the operating parameters of bearings. During the lubrication (where dimple depth lies around to the minimum film thickness),

Figure 3 (a) Variation of frictional torque of conventional and textured bearings; (b) variation of bulk temperature rise of stationary races of bearings; (c) vibration of conventional (non-textured) race bearing in time domain; (d) vibration of conventional race bearing in frequency domain; (e) vibration of textured race bearing in time domain; (f) vibration of textured race bearing in frequency domain

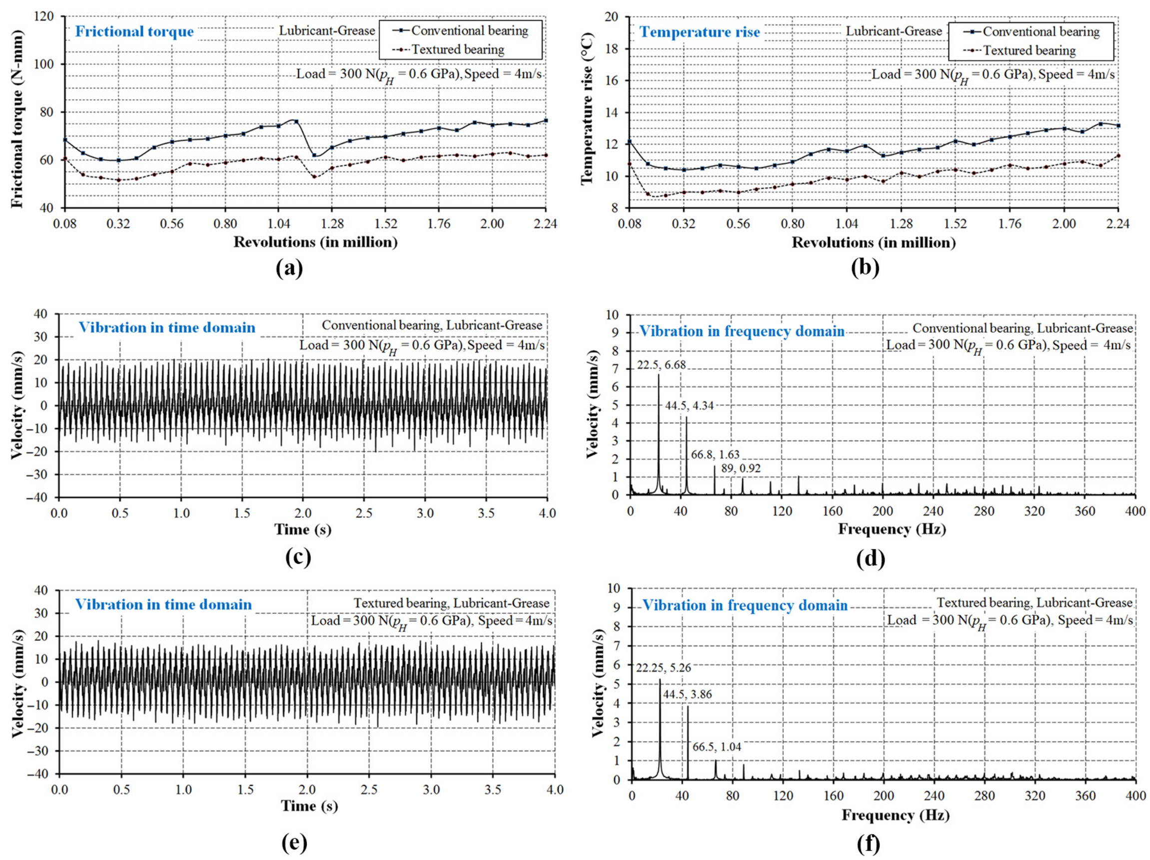
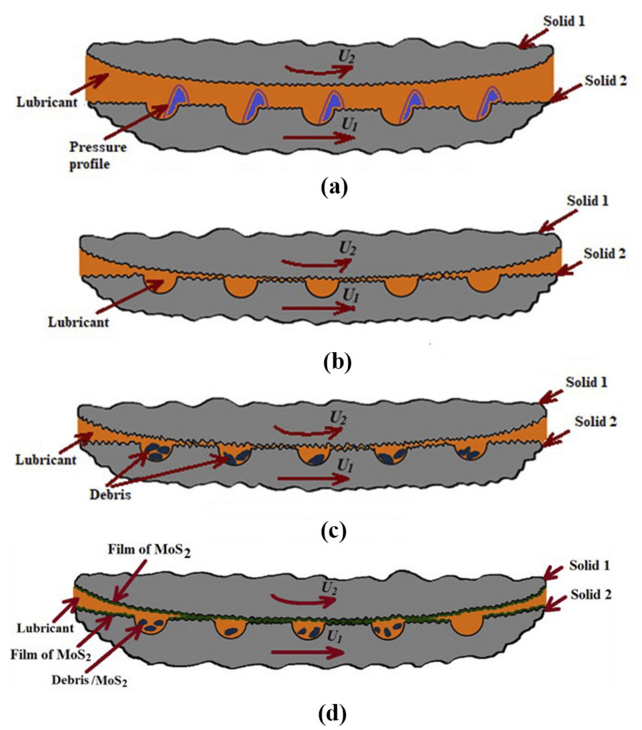


Figure 4 Possible mechanisms associated at the textured contacts leading to improvement in the performance behaviours



Notes: (a) Inumerable micro - hydrodynamic bearings; (b) micro-lubricant reserviros; (c) micro-debris trappers; (d) tribo-film formation

the pair of dimpled surface (in this case stationary race) and running counter surface (in this case balls) leads to the formation of innumerable micro-hydrodynamic bearings [refer to Figure 4(a)]. The pressures generated at innumerable locations in tiny hydrodynamic bearings support the loaded solid in the floating condition over the thin film. In this way, the physical contacts between the solids (in present case it is balls and textured race) get avoided. This leads in the improvement of tribological (reduction in frictional torque) and dynamic (reduction in vibration due to increased damping in presence of fluid film at contacts) behaviours of ball bearings. In case of insufficient lubricating film formation due to the scarcity of lubricant and/or operating parameter (i.e. at heavy load and low speed), the physical interactions between the mating solids (balls and conventional race) take place. In this situation, the frictional torque and vibration enhance in the conventional ball bearing. But in case of textured bearing (in the presence of dimples at race), frictional torque and vibration both reduce because of smearing of lubricant lying within the innumerable dimples [refer to Figure 4(b)]. Moreover, the wear debris generated because of the physical interaction (asperity to asperity contacts) of mating solids get trapped in the micro-reservoirs (i.e. dimples) as schematically shown in Figure 4(c). This also helps in reducing the wear at the solids interfaces.

The MoS_2 particles present in the grease also get settled in dimples and get smeared on races and over the ball surfaces [refer to Figure 4(d)], which provides formation of tribo-film. This also contributes in improving the tribo-dynamic behaviours of ball bearings. Hence, it is understood that the synergistic roles of texture and MoS_2 have led to the improvement in the performance behaviours of texture bearing in comparison to conventional one.

Figure 5 substantiates the understanding about the better retainability of grease at the textured race. The thermographs in Figure 6(a) reveal the regions/locations of high and low temperatures on the races. The high temperature location was found in the region where grease got deposited because of the continuous motion of balls during the operation of bearings. The smeared grease soap deposited away from the balls' track did not get cooled quickly, hence, its location shows high temperature region. It can be observed in Figure 6(a) that in comparison to conventional bearing the textured bearing yields better retainability of grease at the moving race. This finding supports the increase in the lubricant's availability at the moving race of textured bearing as compared to conventional bearing. The SEM images presented in Figure 6(b) show deep scratches (abrasion marks) on the races of conventional race in comparison to textured race. This also substantiates improvement in the tribological performance with textured race. It is understood that in case of conventional race, the debris generated at the contact caused abrasion marks on the race. However in

Figure 5 Photographic views of conventional and textured races after the experiments [load = 300 N (p_H = 0.6 GPa), speed = 4 m/s]

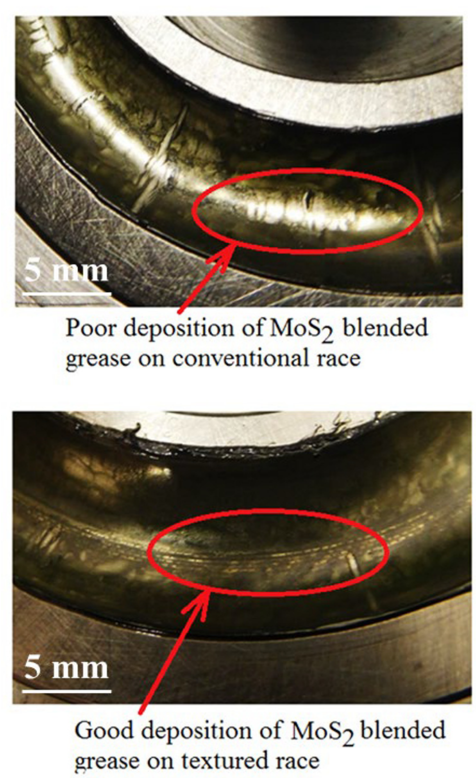


Figure 6 (a) Thermography images of rotating races of conventional and textured bearings for demonstrating the retainability of grease layers after 2.24 million revolutions; (b) SEM images of stationary races of conventional and textured bearings after 2.24 million revolutions [load = 300 N (p_H = 0.6 GPa), speed = 4 m/s]

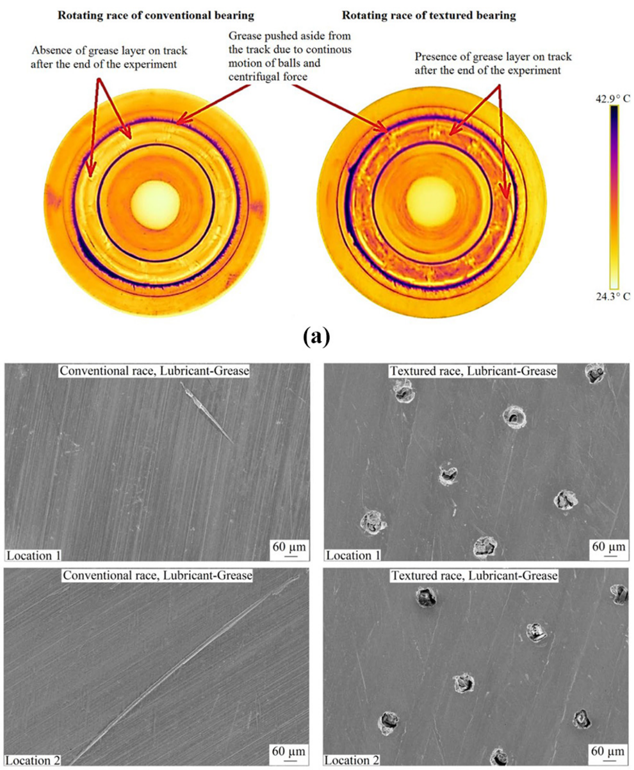
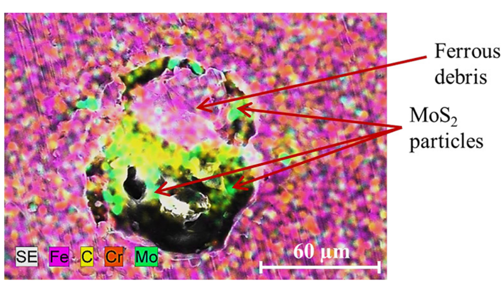


Figure 7 EDX of a dimple [load = 300 N (p_H = 0.6 GPa), speed = 4 m/s]



case of textured race, the debris generated at the contact got trapped within the dimples of texture. Figure 7 shows trapped ferrous debris and few MoS_2 particles in a dimple of texture. It provides the photographic evidence pertaining to trapping of debris/contaminants.

3.2 Performance behaviours of bearings operated in dry condition

The conventional and textured ball bearings were also tested under dry condition (i.e. without lubricant) to observe the comparative surface failures of races and balls. After 0.06 million revolutions, frictional torque and temperature rise in conventional bearing reached 360 N-mm and 29°C, respectively, however the corresponding values recorded with textured bearing were 540 N-mm and 42°C. The SEM images of races and balls are shown in Figure 8. It can be seen that damage of textured race is comparatively more than the race of conventional bearing. Similarly, ball surface of textured bearing got more damaged in comparison to conventional bearing. It is understood that damage on textured race happened because of severe cutting/abrasion by hardened edges of dimples. The weights of assembly (cage and balls) before and after the experiments for each set of bearings were recorded, which have been listed in Table III. It is worth noting here that before the experiment, it was not possible for the authors to remove the balls (without damage of cage and balls) from cage for weighing separately because of assembly concerns. Increase in the weight loss of assembly (cage + balls) of textured bearing is about 3 times as compared to conventional bearing. This reveals that running the textured ball bearing in dry condition is detrimental compared to conventional bearing. It is understood that textured race bearing should not be operated without lubricant.

4. Conclusions

Based on the experimental investigations with conventional and textured ball bearings operated mainly under the starved

Figure 8 SEM images of races and balls of dry run ball bearings [load = 300 N(p_H = 0.6 GPa), speed = 4 m/s]

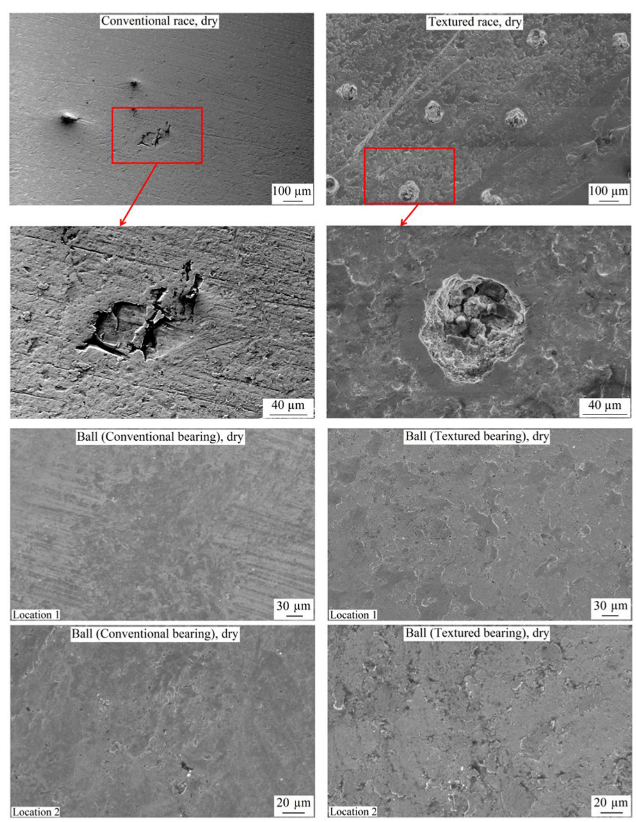


Table III Weight loss of assembly (cage + balls)

S. No.	Type of bearing	Weight of assembly (cage and balls) before the experiments (g)	Weight of assembly (cage and balls) after the experiments (g)	Loss of weight (mg)
1	Conventional bearing (without texture on any component)	135.850	135.599	251
2	Textured bearing (with textured stationary race)	135.844	135.063	781

lubricating condition, the following conclusions have been drawn:

- Textured race bearing yields substantial reduction in frictional torque and decrease in vibration in comparison to conventional (non-textured) raced bearings.
- Significant reduction in bulk temperature rise of stationary race is observed in presence of texture.
- Better retainability of lubricant is found on both the races of textured bearing.
- Operating the textured ball bearing without lubricant is detrimental.
- MoS_2 blended grease generates better tribo-film in textured bearing compared to conventional one.

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