

TRIBO-PERFORMANCE STUDIES OF TEXTURED CONCENTRATED CONTACTS AT HEAVY LOADS USING NANO-LUBRICANTS

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by

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Dedicated to

*My **parents**, my wife **Anpurna**, and my sons **Bhavya & Rudra***

Certificate

This is to certify that the thesis entitled "**Tribo-performance Studies of Textured Concentrated Contacts at Heavy Loads using Nano-lubricants**" is being submitted by **Mr Rameshwar Chaudhary** to the **Indian Institute of Technology Delhi**, New Delhi, India, for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him under our guidance and supervision. The candidate has fulfilled the requirements for the submission of this research work for his doctoral thesis. In our opinion, this thesis has attained the standard needed for awarding a PhD degree from this institute. As per our awareness, the results in this thesis have not been submitted in part or in full to any other university or institute for awarding any degree or diploma.



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(Rameshwar Chaudhary)

Abstract

There is a growing demand for energy-efficient and high-power density concentrated contacts for hard-working machines and mechanical systems. Therefore, the concentrated contacts found in the machine elements, such as rolling bearings, gears, cam-followers, tractive drives etc., are expected to work efficiently in elevated/severe operating conditions. Since the last couple of decades, several techniques, i.e., surface heat treatments, hard coatings, use of additives in lubricant, nano-lubricants, surface polishing, new materials etc., are being employed by researchers/engineers time-to-time to enhance the tribo-performance behaviours of lubricated concentrated line/point contacts. Recently, surface texture has emerged as a viable technology employing which investigators are exploring to improve the tribo-dynamic performance behaviours of the concentrated contacts. Moreover, it is worth noting here that since the researchers are also making recent past attempts to use nano-lubricants to explore and address the concerns related to starved lubrication. Nano-additives involving CuO, carbon nanotubes, graphene oxides, boron nitrides, metal oxides, PTFE and metal sulfide particles etc., have been widely employed in the explorations for improving the tribo-performance behaviours. It is mainly observed that the roles of surface textures have been experimentally studied for the performance behaviours of lubricated line/point contacts at low to medium loads (characterized by Hertzian pressure varying in the range of 0.2-1.5 GPa) and rolling/sliding speeds (0.02 to 1 m/s) under the reciprocating and unidirectional motions. Therefore, the objectives of this research work have been set to explore to reduce the friction and wear and to increase the lubricating film formation behaviours at the textured line and points contacts operating at a wide range of loads ($P_H = 0.20$ to 3.5 GPa) under reciprocating (0.2-0.4 m/s) and unidirectional speeds (up to 3 m/s) using nano oils and greases.

The tribo-performance behaviours of lubricated textured point contacts have been explored at relatively high contact loads (up to 3 GPa) under reciprocating motion (0.2 and 0.4 m/s) employing low ($\nu_{@40^0\text{C}}=100$ cSt) and high ($\nu_{@40^0\text{C}}=422$ cSt) viscous oils as well as MoS₂ and PTFE nano oils. In this experimental study, two contacts (flat conventional surface vs. polished ball and textured flat surface vs. polished ball surface) have been created to investigate friction, wear, and contact potential (the ability for film formation). In the presence of texture at the concentrated contacts, the coefficient of friction and wear has reduced considerably with high viscous oil, irrespective of operating parameters. However, low viscous oil has increased wear under identical operating parameters. The contact potential (an indirect indication of film formation during the running-in period) in the texture's presence develops rapidly compared to the conventional surface with both oils. It has demonstrated a reduction in the running-in period in the presence of textures at the contacts. Moreover, better tribological performances have been achieved with PTFE nano oil compared to MoS₂ nano oil. Tribo-performance evaluations of reciprocating lubricated concentrated line contacts have also been presented herein, employing the synergistic presence of surface texture and MoS₂ and PTFE nano oils. Substantial reductions in friction coefficient (up to 48%) and specific wear rate (of worn rollers) have been found in the combined texture and nano oils at the concentrated line contacts. Moreover, a significant increase in the contact potential (an indication of film formation ability) has also been noticed in the presence of texture and base oils.

Tribo-behaviours of grease lubricated textured point contacts were experimentally explored at heavy loads (characterized in terms of Hertzian pressure, $P_H=1.5\text{-}3.0$ GPa) and relatively low sliding speeds (0.2 and 0.4 m/s) under the linear reciprocating motion employing lithium based low and high consistency greases as well as MoS₂ and PTFE nano greases. Using a controlled stress rheometer, the effects of grease consistency on the greases' rheological

behaviours have also been found at two temperatures, 25°C and 80°C. Overall, textured concentrated contacts yielded a low coefficient of friction (reduction of up to 24.6%), reduced specific wear rate of the ball (decrease of up to 89.5%) and better development of contact potential compared to conventional contacts. The transmission electron microscopy (TEM) of used greases collected from textured contacts revealed less degradation in soap fibres. Moreover, the X-ray photoelectron spectroscopy (XPS) revealed the formation of ferric oxide (Fe_2O_3) and ferrous-ferric oxide (Fe_3O_4) protective chemical films on the worn surfaces of balls of the conventional and textured contacts. However, it is also found that friction coefficient and specific wear rate of worn balls reduced considerably in the presence of texture and nanoparticle (MoS_2 and PTFE) blended greases at the concentrated contacts irrespective of operating parameters. The coefficient of friction reduced up to 31% at concentrated textured contact lubricated with MoS_2 nano grease. Moreover, it reduces up to 30% when lubricated with PTFE nano grease. The specific wear rate of worn balls of concentrated textured contact was reduced to 94% with MoS_2 nano grease and 96% with PTFE nano grease.

The effect of MoS_2 and PTFE nano oil (MoS_2 and PTFE nanoparticle blended in oil) on the tribo-behaviours of textured point contacts have been explored at moderate loads ($P_H=0.5$ and 0.8 GPa) in different lubrication regimes. Two contact configurations (grounded disc vs ball and textured disc vs ball) have been employed to experimentally investigate the friction and wear under boundary, mixed and elastohydrodynamic lubrication regimes. A femtosecond pulsed laser has been used to create the surface texture (dimples) of two sizes and dimple area densities. It is found that friction coefficient and wears tracks' width are reduced due to the combined effect of texture and nano lubricating oil at the concentrated point contact irrespective of operating parameters. The textured concentrated point contact lubricated with MoS_2 and PTFE nano oil yielded a lower friction coefficient than conventional contact in both boundary and mixed boundary regimes. Moreover, the reduction in friction coefficient was

observed more in the boundary regime than in the mixed regime due to the acting of dimples as lubricant reservoirs. The optical images of worn balls and discs, EDS of the worn textured surface and AFM images have been presented to describe the associated mechanism.

सार

कड़ी मेहनत करने वाली मशीनों और यांत्रिक प्रणालियों के लिए ऊर्जा-कुशल और उच्च-शक्ति घनत्व केंद्रित संपर्कों की मांग बढ़ रही है। इसलिए, मशीन के तत्वों में पाए जाने वाले केंद्रित संपर्क, जैसे कि रोलिंग बियरिंग्स, गियर्स, कैम-फॉलोअर्स, ट्रैक्टिव ड्राइव आदि, से उच्च/गंभीर परिचालन स्थितियों में कुशलता से काम करने की उम्मीद की जाती है। पिछले कुछ दशकों से, कई तकनीकों, जैसे, सतही गर्मी उपचार, कठोर कोटिंग्स, स्नेहक में एडिटिव्स का उपयोग, नैनो-लुब्रिकेंट्स, सतह पॉलिशिंग, नई सामग्री आदि, समय-समय पर शोधकर्ताओं/इंजीनियरों द्वारा नियोजित किए जा रहे हैं। लुब्रिकेटेड कंसट्रेंट लाइन/पॉइंट कॉन्टैक्ट्स के ट्राइबो-परफॉर्मेंस बिहेवियर को बढ़ाएं। हाल ही में, सतह की बनावट एक व्यवहार्य तकनीक के रूप में उभरी है, जिसका उपयोग जांचकर्ता केंद्रित संपर्कों के ट्राइबो-डायनामिक प्रदर्शन व्यवहार को बेहतर बनाने के लिए कर रहे हैं। इसके अलावा, यहां यह ध्यान देने योग्य है कि शोधकर्ता हाल के दिनों में भूखे स्नेहन से संबंधित चिंताओं का पता लगाने और उन्हें संबोधित करने के लिए नैनो-स्नेहक का उपयोग करने के प्रयास कर रहे हैं। नैनो-एडिटिव्स जिनमें CuO , कार्बन नैनोट्यूब, ग्राफीन ऑक्साइड, बोरॉन नाइट्राइड, मेटल ऑक्साइड, PTFE और मेटल सल्फाइड कण आदि शामिल हैं, को व्यापक रूप से ट्राइबो-प्रदर्शन व्यवहार में सुधार के लिए अन्वेषण में नियोजित किया गया है। यह मुख्य रूप से देखा गया है कि सतह की बनावट की भूमिकाओं का प्रयोगात्मक रूप से निम्न से मध्यम भार ($P_H = 0.2\text{-}1.5\text{ GPa}$ की सीमा में भिन्न) और रोलिंग / स्लाइडिंग गति पर चिकनाई लाइन / बिंदु संपर्कों के प्रदर्शन व्यवहार के लिए किया गया है (0.02 से 1 m/s) पारस्परिक और एकदिश गति के तहत। इसलिए, इस शोध कार्य के उद्देश्यों को घर्षण और पहनने को कम करने और टेक्सचर्ड लाइन पर लुब्रिकेटिंग फिल्म निर्माण व्यवहार को बढ़ाने के लिए निर्धारित किया गया है और लोड की एक विस्तृत श्रृंखला ($P_H = 0.20$ से 3.5 GPa) पर काम कर रहे संपर्कों को इंगित करता है। नैनो-ऑयल और ग्रीस का उपयोग करते हुए पारस्परिक (0.2-0.4 m/s) और यूनिडायरेक्शनल गति (3 m/s तक)।

लुब्रिकेटेड टेक्सचर पॉइंट कॉन्टैक्ट्स के ट्राइबो-परफॉर्मेंस बिहेवियर को रिसीप्रोकेटिंग मोशन (0.2 और 0.4 m/s) के तहत कम (@40°C = 100 cSt) और हाई के तहत अपेक्षाकृत उच्च कॉन्टैक्ट लोड (3 GPa तक) पर खोजा गया है। (40°C = 422 cSt) चिपचिपा तेल और साथ ही MoS_2 और PTFE नैनो-तेल। इस प्रायोगिक अध्ययन में, घर्षण,

पहनने और संपर्क क्षमता (फिल्म निर्माण की क्षमता) की जांच के लिए दो संपर्क (सपाट पारंपरिक सतह बनाम पॉलिश की गई गेंद और बनावट वाली सपाट सतह बनाम पॉलिश की गई गेंद की सतह) बनाए गए हैं। संकेंद्रित संपर्कों पर बनावट की उपस्थिति में, उच्च चिपचिपा तेल के साथ घर्षण और पहनने का गुणांक काफी कम हो गया है, परिचालन मापदंडों के बावजूद। हालांकि, कम चिपचिपा तेल ने समान ऑपरेटिंग मापदंडों के तहत पहनने में वृद्धि की है। बनावट की उपस्थिति में संपर्क क्षमता (रनिंग-इन अवधि के दौरान फिल्म निर्माण का एक अप्रत्यक्ष संकेत) दोनों तेलों के साथ पारंपरिक सतह की तुलना में तेजी से विकसित होती है। इसने संपर्कों में बनावट की उपस्थिति में चलने की अवधि में कमी का प्रदर्शन किया है। इसके अलावा, MoS₂ नैनो-तेल की तुलना में PTFE नैनो-तेल के साथ बेहतर जनजातीय प्रदर्शन हासिल किया गया है। सतही बनावट और MoS₂ और PTFE नैनो तेलों की सहक्रियात्मक उपस्थिति को नियोजित करते हुए, पारस्परिक स्नेहक केंद्रित लाइन संपर्कों के ट्राइबो-प्रदर्शन मूल्यांकन भी यहां प्रस्तुत किए गए हैं। केंद्रित लाइन संपर्कों पर बनावट और नैनो-तेल की संयुक्त उपस्थिति में घर्षण गुणांक (48% तक) और विशिष्ट पहनने की दर (पहने रोलर्स) में पर्याप्त कमी पाई गई है। इसके अलावा, बनावट और बेस ऑयल की उपस्थिति में संपर्क क्षमता (फिल्म निर्माण क्षमता का एक संकेत) में उल्लेखनीय वृद्धि भी देखी गई है।

भारी भार (हर्ट्जियन दबाव, $P_H = 1.5-3.0$ GPa के संदर्भ में विशेषता) और लिथियम को नियोजित करने वाली रैखिक पारस्परिक गति के तहत अपेक्षाकृत कम स्लाइडिंग गति (0.2 और 0.4 m/s) पर ग्रीस स्नेहक बनावट बिंदु संपर्कों के ट्राइबो-व्यवहारों का प्रयोगात्मक रूप से पता लगाया गया था। आधारित कम और उच्च स्थिरता ग्रीस के साथ-साथ MoS₂ और PTFE नैनो ग्रीस। नियंत्रित स्ट्रेस रियोमीटर का उपयोग करते हुए, ग्रीस के रियोलॉजिकल व्यवहार पर ग्रीस की स्थिरता का प्रभाव भी दो तापमानों, 25 डिग्री सेल्सियस और 80 डिग्री सेल्सियस पर पाया गया है। कुल मिलाकर, बनावट वाले संकेंद्रित संपर्कों में घर्षण का कम गुणांक (24.6% तक की कमी), गेंद की विशिष्ट पहनने की दर (89.5% तक की कमी) और पारंपरिक संपर्कों की तुलना में संपर्क क्षमता का बेहतर विकास हुआ। बनावट वाले संपर्कों से एकत्र किए गए प्रयुक्त ग्रीस के ट्रांसमिशन इलेक्ट्रॉन माइक्रोस्कोपी (टीईएम) ने साबुन के रेशों में कम गिरावट का खुलासा किया। इसके अलावा, एक्स-रे फोटोइलेक्ट्रॉन स्पेक्ट्रोस्कोपी (XPS) ने पारंपरिक और बनावट वाले संपर्कों की गेंदों की घिसी हुई सतहों पर फेरिक ऑक्साइड (Fe₂O₃) और फेरस-फेरिक ऑक्साइड

(Fe₃O₄) सुरक्षात्मक रासायनिक फिल्मों के गठन का खुलासा किया। हालांकि, यह भी पाया गया है कि घर्षण गुणांक और घिसी हुई गेंदों की विशिष्ट पहनने की दर बनावट और नैनोपार्टिकल (MoS₂ और PTFE) मिश्रित ग्रीस की उपस्थिति में काफी कम हो जाती है, जो परिचालन मापदंडों के बावजूद केंद्रित संपर्कों पर होती है। MoS₂ नैनो ग्रीस से लुब्रिकेटेड टेक्सचर्ड कॉन्सट्रैटेड कॉन्टैक्ट पर घर्षण का गुणांक 31% तक कम हो गया। इसके अलावा, PTFE नैनो ग्रीस के साथ चिकनाई करने पर यह 30% तक कम हो जाता है। केंद्रित बनावट वाले संपर्क की घिसी हुई गेंदों की विशिष्ट पहनने की दर को MoS₂ नैनो ग्रीस के साथ 94% तक और PTFE नैनो ग्रीस के साथ 96% तक कम किया गया था।

MoS₂ और PTFE नैनो तेल (MoS₂ और PTFE नैनोपार्टिकल मिश्रित तेल) के बनावट बिंदु संपर्कों के ट्राइबो-व्यवहार पर विभिन्न स्नेहन व्यवस्थाओं में मध्यम भार ($P_H = 0.5$ और 0.8 GPa) पर पता लगाया गया है। दो प्रकार के संपर्क विन्यास (ग्राउंडेड डिस्क बनाम बॉल और टेक्सचर्ड डिस्क बनाम बॉल) को प्रयोगात्मक रूप से घर्षण की जांच करने और सीमा, मिश्रित और इलास्टोहाइड्रोडायनामिक स्नेहन व्यवस्था के तहत पहनने के लिए नियोजित किया गया है। दो आकारों और डिंपल क्षेत्र घनत्व की सतह बनावट (डिंपल) बनाने के लिए एक फेमटोसेकंड स्पंदित लेजर का उपयोग किया गया है। यह पाया गया है कि घर्षण गुणांक और वियर ट्रैक्स की चौड़ाई कम हो जाती है, क्योंकि बनावट और नैनो स्नेहक तेल के संयुक्त प्रभाव के कारण केंद्रित बिंदु संपर्क पर परिचालन मापदंडों के बावजूद कम हो जाता है। MoS₂ और PTFE नैनो तेल के साथ चिकनाई वाले बनावट वाले केंद्रित बिंदु संपर्क ने सीमा और मिश्रित सीमा व्यवस्था दोनों में पारंपरिक संपर्क की तुलना में कम घर्षण गुणांक प्राप्त किया। इसके अलावा, घर्षण गुणांक में कमी मिश्रित शासन की तुलना में सीमा शासन में स्नेहक जलाशयों के रूप में डिंपल के अभिनय के कारण अधिक देखी गई थी। संबंधित तंत्र का वर्णन करने के लिए घिसी हुई गेंदों और डिस्क की ऑप्टिकल छवियां, घिसी हुई बनावट वाली सतह के ईडीएस और एएफएम छवियों को प्रस्तुत किया गया है।

Contents

Certificate	i
Acknowledgements	ii
Abstract	v
Contents	xii
List of Figures	xviii
List of Tables	xxv
Nomenclature	xxvii
Chapter-1 Introduction	1
1.1 Background	1
1.2 Lubrication regime	3
1.3 Techniques used to improve the tribological performances	4
1.3.1 Use of additives in lubricants	4
1.3.2 Use of micro/nano materials in lubricants	5
1.3.3 Textures at the interface	6
1.4 Scope of study	7
1.5 Organization of thesis	8
Chapter-2 Literature Review	9
2.1 Tribo-performance of oil lubricated textured concentrated contacts	9
2.1.1 Theoretical/numerical studies with oil lubricated textured	

concentrated contacts	9
2.1.2 Experimental studies with oil lubricated textured concentrated contacts	10
2.1.3 Experimental analysis of oil lubricated textured concentrated line contacts	17
2.2 Tribo-performance of grease lubricated textured concentrated contacts	20
2.3 Tribological behaviours of nano oil lubricated concentrated contacts	22
2.3.1 Nano oil lubricated concentrated contacts	23
2.3.2 Nano oil lubricated textured concentrated contacts	25
2.4 Tribological behaviours of nano grease lubricated concentrated contacts	27
2.4.1 Tribo-performance of nano grease lubricated concentrated contact	27
2.4.2 Nano grease lubricated textured concentrated contact	28
2.5 Summary of literature review and research gap	30
2.6 Research gap	30
2.7 Objectives of the study	31
Chapter-3 Tribological performances of heavily loaded oil lubricated point contacts: textured vs. conventional	33
3.PART-A	
Tribological studies of low and high viscous oils lubricated heavily loaded textured point contacts under reciprocating motion	33
3.A.1 Experimental detail	34
3.A.1.1 Contact configuration	35
3.A.1.2 Creation of texture and characterization of surfaces	36
3.A.1.3 Surface wettability	38
3.A.1.4 Micro-hardness	39

3.A.1.5 Lubricating oil	41
3.A.1.6 Methods of performance measurement	41
3.A.1.7 Experimental procedure	44
3.A.2 Results and discussion	45
3.A.2.1 Coefficient of friction	45
3.A.2.2 Wear	48
3.A.2.3 Contact potential	52
3.A.3 Concluding remarks	56
3.PART-B	
Tribological studies of lubricated textured point contacts using MoS₂ and PTFE nano oils under the reciprocating motion	57
3.B.1 Experimental detail	57
3.B.1.1 MoS ₂ and PTFE nanomaterials	57
3.B.1.2 Preparation of nano oils	58
3.B.1.3 Creation of texture and characterization of surfaces	59
3.B.2 Results and discussion	61
3.B.2.1 Coefficient of friction	61
3.B.2.2 Wear	64
3.B.2.3 Contact potential	72
3.B.3 Concluding remarks	74
Chapter-4 Tribo-performances of moderately loaded oil lubricated line contacts: textured vs. conventional	75
4.1 Experimental detail	75
4.1.1 Experimental setup and contact configuration	75
4.1.2 Preparation of textured surface and characterization	77
4.1.3 Methods to measure tribological performance	79

4.1.4 Experimental procedure and analysis process	81
4.2 Results and discussion	82
4.2.1 Coefficient of friction at constant load	82
4.2.2 Friction coefficient at varying speed	86
4.2.3 Wear	90
4.2.4 contact potential	95
4.2.5 SEM-EDS studies and elemental mapping of worn surfaces	98
4.3 Concluding remarks	102
Chapter-5 Tribological performances of heavily loaded grease lubricated point contacts: textured vs. conventional	103
5.PART-A	
Tribo-behaviours of textured point contacts lubricated with low and high consistency lithium greases under reciprocating motion	103
5.A.1 Experimental detail	104
5.A.1.1 Experimental test rig and contact configuration	104
5.A.1.2 Preparation and characterization of conventional and textured surfaces	105
5.A.1.3 Selection of greases and characterization	107
5.A.1.4 Experimental procedure	110
5.A.2 Results and discussion	111
5.A.2.1 Coefficient of friction	111
5.A.2.2 Wear	117
5.A.2.3 Contact potential	124
5.A.3 Concluding remarks	128

5.PART-B

Tribo-performances of reciprocating point contacts using a texture and MoS₂/PTFE nanoparticle blended greases	129
5.B.1 Experimental detail	130
5.B.1.1 Preparation of nano materials blended grease	131
5.B.1.2 Creation of texture and characterization of surfaces	132
5.B.2 Results and discussion	132
5.B.2.1 Coefficient of friction	133
5.B.2.2 Wear	135
5.B.2.3 Contact potential	143
5.B.3 Concluding remarks	145
Chapter-6 Tribological performances of nano oils lubricated point contacts : unidirectional rolling/sliding motion	146
6.1 Experimental description	147
6.1.1 Tribological test machine	147
6.1.2 Creation of texture and characterization of surfaces	148
6.1.3 Preparation of nano oil with MoS ₂ nanoflakes and PTFE nanoparticle	149
6.1.4 Methods of performance measurement	150
6.1.5 Experimental procedure	150
6.2 Results and discussion	151
6.2.1 Friction coefficient with the influence of parameter	151
6.2.2 Wear	158
6.2.3 EDS and AFM investigation of worn surfaces	161
6.3 Concluding remarks	162
Chapter-7 Conclusions and scope of further research	163

7.1 Conclusions	165
7.1.1 Tribological performances of heavily loaded oil lubricated point contacts: textured vs. conventional	165
7.1.2 Tribo-performances of moderately loaded oil lubricated line contacts: textured vs. conventional	167
7.1.3 Tribological performances of heavily loaded grease lubricated point contacts: textured vs. conventional	168
7.1.4 Investigation of the tribo-performances of unidirectional rolling/sliding point contacts using nano oils	170
7.2 Scope of further research	169
References	172

List of Figures

Fig. No.	Description	Page No.
1.1	Different lubricated concentrated contacts found in machine elements	2
1.2	Typical pressure distribution in an EHL contact	2
1.3	Stribeck curve for lubricated contacts demonstrating the different regimes of lubrication	4
1.4	Illustration of the mechanisms in the presence of micro/nano particles in lubricants; (a) Protective tribo-film formation; (b) Rolling effect; (c) Mending effect; (d) Polishing effect	6
1.5	Laser textured dimple (a) SEM image (b) 3D microscopic image of one dimple	7
2.1	Friction behaviours of concentrated lapped and textured concentrated contacts	12
2.2	Specific wear rate of balls of lapped and textured concentrated contacts	13
2.3	Micro-geometries of surface textures: (a) circular, (b) elliptical, (c) triangular, (d) rectangular, (e) groove, and (f) chevron	21
2.4	Friction coefficient variation with nano oil lubrication of contacts under unidirectional and reciprocating motions	24
2.5	Friction coefficient variations with nano oil lubrication	25
2.6	Electrical contact resistance existing between conventional and textured teeth of gearsets in lubricated cases	29
3.1	(a) Photographic view of reciprocating test rig; (b) Schematic illustration of reciprocating point contact configuration	35
3.2	SEM micrographs of laser-textured surfaces :(a) view of un-lapped dimples (b) view of lapped dimples and (c) 2-D surface topography of textured flat plate	37
3.3	X-ray diffraction patterns of conventional and textured specimen plates	38
3.4	Micro-hardness measured at different points around a dimple	40

3.5	Microstructure of textured surface	41
3.6	Detail of wear volume calculation of ball	43
3.7	Illustration of tribo-contact parallel to a resistance	44
3.8	Coefficient of friction variation during reciprocating sliding motion with several working parameters (a) $U_s=0.2$ m/s Oil A (b) $U_s=0.4$ m/s Oil A (c) $U_s=0.2$ m/s Oil B (d) $U_s=0.4$ m/s Oil B	47
3.9	Specific wear rates of the ball during reciprocating sliding contacts with several operating parameters (a) $U_s=0.2$ m/s Oil A (b) $U_s=0.4$ m/s Oil A (c) $U_s=0.2$ m/s Oil B (d) $U_s=0.4$ m/s Oil B	49
3.10	Comparisons of wear tracks and corresponding wear scar on balls [$U_s=0.2$ m/s, Oil-A]	51
3.11	Comparisons of wear tracks and corresponding wear scar on balls [$U_s=0.2$ m/s, Oil-A]	52
3.12	Contact potential between ball and plate at sliding contacts in reciprocating motion with a combination of operating parameters of oil A	54
3.13	Contact potential between ball and plate at sliding contacts in reciprocating motion with a combination of operating parameters of oil B	55
3.14	Micro-images of nanomaterials for dimensional details, (a) SEM images of MoS ₂ flakes; (b) SEM images of PTFE particles; (c) TEM image of MoS ₂ flake; (d) TEM image of PTFE particles	58
3.15	SEM micrograph of grounded and textured surface (a) conventional surface (b) textured surface (c) 2D topography of the textured surface	60
3.16	Friction coefficient variation having conventional and textured contact lubricated with Base and MoS ₂ nano oil at specified sliding speed (a) $U_s=0.1$ m/s, (b) $U_s=0.4$ m/s	62
3.17	Friction coefficient variation having conventional and textured Contact lubricated with Base and PTFE nano oil at specified sliding speed (a) $U_s=0.1$ m/s and (b) $U_s=0.4$ m/s	64
3.18	Specific wear rate variation having conventional and textured contact lubricated with base and MoS ₂ nano oil at specified sliding speed (a) $U_s=0.1$ m/s, (b) $U_s=0.4$ m/s	66
3.19	Specific wear rate variation having conventional and textured contact lubricated with base and PTFE nano oil at specified sliding speed (a) $U_s=0.1$ m/s and (b) $U_s=0.4$ m/s	68

3.20	SEM images of worn balls formed the conventional Contact [$P_H=1.5$ GPa and $U_s=0.1$ m/s]	69
3.21	SEM images of worn balls formed the textured Contact [$P_H=1.5$ GPa, $U_s=0.1$ m/s]	70
3.22	EDS result and elemental mapping characterization of textured surface lubricated with MoS ₂ nano oil	71
3.23	EDS result and elemental mapping characterization of textured surface lubricated with PTFE nano oil	72
3.24	Contact potential between concentrated point contact with specified operating parameters	73
4.1	Experimental rig (a) photographic illustration rig (b) photographic view of specimen holder (c) schematic CAD model of contact configuration (d) schematic model of textured plate and roller	76
4.2	Stribeck curve test profile with varying speed	77
4.3	SEM images of grounded and textured surface (a) grounded surface (b) grounded textured surface (c) 2D surface profile of a grounded textured surface	78
4.4	Calculation of roller's worn volume	79
4.5	Coefficient of friction variation between conventional and textured line contact lubricated with base oil and PTFE nano oil (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.4$ m/s	83
4.6	Coefficient of friction variation between conventional and textured line contact lubricated with base oil and MoS ₂ nano oil (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.4$ m/s	85
4.7	Stribeck curve for conventional and textured line contact lubricated with a base oil and PTFE nano oils	88
4.8	Stribeck curve for conventional and textured line contact lubricated with a base oil and MoS ₂ nano oils	89
4.9	The specific wear rate of roller wear variation between conventional and textured line contact lubricated with a base oil and PTFE nano oil (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.4$ m/s	91
4.10	The specific wear rate of roller wear variation between conventional and textured line contact lubricated with a base oil and MoS ₂ nano oil (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.4$ m/s	92
4.11	Optical micrograph of worn rollers of conventional/textured line contact [$U_s=0.1$ m/s]	93

4.12	Optical micrograph of worn rollers of conventional/textured line contact [$U_s=0.4$ m/s]	94
4.13	Variation in contact potential between concentrated line contact lubricated with base oil and PTFE nano oil	97
4.14	Variation in contact potential between concentrated line contact lubricated with a base oil and MoS ₂ nano oil	98
4.15	EDS analysis and elemental mapping of worn conventional flat surface lubricated with MoS ₂ nano oil [$P_H=0.7$ GPa and $U_s=0.1$ m/s]	99
4.16	EDS analysis and elemental mapping of worn textured flat surface lubricated with MoS ₂ nano oil [$P_H=0.7$ GPa and $U_s=0.1$ m/s]	100
4.17	EDS analysis and elemental mapping of worn conventional flat surface lubricated with PTFE nano oil [$P_H=0.7$ GPa and $U_s=0.1$ m/s]	101
4.18	EDS analysis and elemental mapping of worn conventional flat surface lubricated with PTFE nano oil [$P_H=0.7$ GPa and $U_s=0.1$ m/s]	102
5.1	Description of the experimental setup; (a) photographic view of setup, (b) photographic views of the ball and flat plate in sub-assemblies, (c) schematic view of ball and flat plate assembly	105
5.2	Surface features of flat plate specimens; (a) grounded surface, (b) laser textured surface (before grinding), (c) textured surface (after grinding), (d) enlarged view of a dimple, (e) 2-D surface topography of textured surface (after grinding)	106
5.3	SEM images of grease soap structures; (a) fresh grease-A, (b) used grease-A, (c) fresh grease-B, (d) used grease-B [$P_H=3.0$ GPa, $U_s=0.2$ m/s, conventional contact]	108
5.4	Coefficient of friction comparisons conventional vs. textured; (a) Grease-A, $U_s=0.2$ m/s, (b) Grease-A, $U_s=0.4$ m/s, (c) Grease-B, $U_s=0.2$ m/s, (d) Grease-B, $U_s=0.4$ m/s	114
5.5	Photographic views of grease-B lubricated tracks on conventional and textured flat plate specimens; (a) Conventional Contact, $P_H=1.5$ GPa, $U_s=0.2$ m/s, (b) Conventional Contact, $P_H=3.0$ GPa, $U_s=0.2$ m/s, (c) Textured Contact, $P_H=1.5$ GPa, $U_s=0.2$ m/s, (d) Textured Contact, $P_H=3.0$ GPa, $U_s=0.2$ m/s	115
5.6	Phenomena (innumerable oil reservoirs and debris trappers) responsible for lubrication improvement at the concentrated textured contacts	115

5.7	TEM micrographs of soap fibre structures of fresh and used greases; (a) fresh and used grease-A; (b) fresh and used grease-B [$P_H=3.0$ GPa, $U_s=0.2$ m/s, Conventional Contact]	116
5.8	Comparisons of shear stress vs. shear rate plots of grease-A and grease-B; (a) at 25°C temperature, (b) at 80°C temperature	116
5.9	Specific wear rate comparisons conventional vs. textured; (a) Grease-A, $U_s=0.2$ m/s, (b) Grease-A, $U_s=0.4$ m/s, (c) Grease-B, $U_s=0.2$ m/s, (d) Grease-B, $U_s=0.4$ m/s	120
5.10	XPS spectra of C1s, O1s $\text{Fe}_{2p}/\text{Fe}_{3p}$ obtained from the worn balls' worn surfaces for the lubrication cases with grease-A and grease-B	121
5.11	Comparisons of wear scars of conventional contacts' plates and balls lubricated with grease-A	122
5.12	Comparisons of wear scars of textured contacts' plates and balls lubricated with grease-A	123
5.13	Three dimensional (3D) micrographs of fresh and worn balls [$P_H=2$ GPa, $U_s=0.2$ m/s, grease-A]	124
5.14	Variation of electrical contact potential at conventional and textured contacts at different operating parameters in the presence of grease-A	126
5.15	Variation of electrical contact potential at conventional and textured contacts at different operating parameters in the presence of grease-B	127
5.16	TEM images of MoS_2 flakes and PTFE nanoparticles blended greases	130
5.17	Friction coefficient at conventional and textured contact lubricated with base grease and MoS_2 blended grease (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.3$ m/s	134
5.18	Friction coefficient at conventional and textured contact lubricated with base grease and PTFE blended grease (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.3$ m/s	135
5.19	Specific wear rate at conventional and textured contact lubricated with base grease and MoS_2 blended grease (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.3$ m/s	137
5.20	Specific wear rate at conventional and textured contact lubricated with base grease and PTFE blended grease (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.3$ m/s	138
5.21	Optical micro of worn balls and corresponding wear tracks on flat plate lubricated with base grease at low sliding speed ($U_s=0.1$ m/s)	139

5.22	Optical micro of worn balls and corresponding wear tracks on flat plate lubricated with MoS ₂ grease at low sliding speed ($U_s=0.1$ m/s)	140
5.23	Optical micro of worn balls and corresponding wear tracks on flat plate lubricated with PTFE grease at low sliding speed ($U_s=0.1$ m/s)	141
5.24	EDS elemental mapping and spectra of worn textured surface lubricated with MoS ₂ nanoflakes blended grease	142
5.25	EDS elemental mapping and spectra of worn textured surface lubricated with PTFE nano flakes blended grease	143
5.26	Contact potential at conventional and textured contact lubricated with base grease and MoS ₂ blended grease (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.3$ m/s	144
5.27	Contact potential at conventional and textured contact lubricated with base grease and PTFE blended grease (a) sliding speed, $U_s=0.1$ m/s, (b) sliding speed $U_s=0.3$ m/s	145
6.1	Mini-traction machine (a) Photographic view of MTM-2 (b) Schematic CAD model of contact configuration	148
6.2	Optical micro-images of surfaces (a) Conventional surface (b) Texture-1 (T-1) and (c) Texture-1 (T-2)	149
6.3	Coefficient of friction variation (Stribeck curve) between conventional and textured point contact lubricated with a base oil and MoS ₂ nano oil at 5N ($P_H=0.5$ GPa)	153
6.4	Coefficient of friction variation (Stribeck curve) between conventional and textured point contact lubricated with a base oil and MoS ₂ nano oil at 5N ($P_H=0.8$ GPa)	154
6.5	Coefficient of friction (Stribeck curve) variation between conventional and textured point contact lubricated with a base oil and PTFE nano oil at 5N ($P_H=0.5$ GPa)	156
6.6	Coefficient of friction (Stribeck curve) variation between conventional and textured point contact lubricated with base oil and PTFE nano oil at 5N ($P_H=0.8$ GPa)	157
6.7	Wear scar width of the ball and corresponding disc lubricated with base oil and MoS ₂ nano oil	158
6.8	Wear scar width of the ball and corresponding disc lubricated with base oil and PTFE nano oil	159

6.9	Optical micrograph of the ball and corresponding disc lubricated with the base oil	160
6.10	Optical micrograph of the ball and corresponding disc lubricated with MoS ₂ nano oil	160
6.11	Optical micrograph of the ball and corresponding disc lubricated with PTFE nano oil	161
6.12	EDS elemental mapping of worn textured disc lubricated with MoS ₂ nano oil	162
6.13	EDS elemental mapping of worn textured disc lubricated with PTFE nano oil	162
6.14	AFM 3D image of disc wear track lubricated with base oil [surface roughness of line profile = 48 nm]	163
6.15	AFM 3D image of disc wear track lubricated with MoS ₂ nano oil [surface roughness of line profile = 23 nm]	163
6.16	AFM 3D image of disc wear track lubricated with PTFE nano oil [surface roughness of line profile = 19 nm]	164

List of Tables

S. No.	Description	Page No.
2.1	Summary of tribological investigations performed with textured point contacts	14
2.2	Summary of tribological investigations carried out with textured line contacts	18
2.3	Summary of tribological investigations carried out with textured contacts in the presence of nano-materials	26
3.1	Operating parameters	36
3.2	Specification of conventional and textured surface	38
3.3	Contact angle between oil droplet and specimen surface	39
3.4	Values of hardness and modulus at various points	40
3.5	Properties of lubricating oils	41
3.6	Dimensional details of nanomaterials	58
3.7	Properties of lubricating oils	59
3.8	Specification of the conventional and textured surface	60
4.1	Operating parameters	77
4.2	Surface parameter of ground and textured surface	78
5.1	Specifications of the ground plate and grounded textured plate surfaces	107
5.2	Properties of grease samples	109
5.3	Operating parameters	110
5.4	Atomic percentage (wt%) of worn balls' surface	118
5.5	Dimensional details of nanoparticle	129
5.6	Properties of nano-grease samples	131

5.7	Specification of the conventional and textured surface	132
6.1	Operating parameters for unidirectional rolling-sliding motion	148
6.2	Specification of the conventional and textured surface of MTM discs	149
6.3	Properties of nano oils	150

Nomenclature

f	Frequency, Hz
F	Friction force, N
P_H	Hertzian pressure, GPa
R_a	Average roughness, μm
R_q	Root mean square (rms) roughness, μm
s	Stroke, mm
T	Temperature, $^{\circ}\text{C}$
U_s	Sliding speed, m/s
η	Viscosity of lubricant, Pa-s
ν	Kinematic viscosity, mm^2/s
ρ	Lubricant density, kg/m^3
μ	Coefficient of friction
d	Wear scar diameter, mm
F	Friction force, N
h_{min}	Minimum film thickness, m