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Effect of coatings on rolling contact fatigue and tribological parameters of rolling/sliding contacts under dry/lubricated conditions: a review

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Abstract. The application of coating gets exceptional importance since it improves the tribological properties of the contacting surfaces. Different input parameters like coating deposition processes, coating material properties and its thickness, use of lubricant and its additives, surface roughness and temperature affect the tribological properties and the rolling contact fatigue (RCF) life of coated rolling and sliding contact elements. In this paper, an attempt has been made to review for the clear understanding of the effect of these input parameters on the RCF life and tribological performance of coated rolling and sliding contact elements. It has been observed that coating deposition process must be chosen based on technical and economic aspects. Among the different techniques, thermal spraying technique is cost effective, and it also provides better bonding strength, which improves the RCF life in comparison with other techniques. Similarly, the effect of other input parameters has been reviewed and possible combination of the input parameters that help improve the performance of coated contacting elements summarized. Furthermore, the current status of research and the scope of future work to be carried out, in this area, have been outlined.

Keywords. Rolling contact fatigue life; coating; friction; wear; thermal spraying.

1. Introduction

Currently, coating technology and its application have been alluring the remarkable attention of researchers all over the world. The usage of the coatings in case of contacting surfaces is increasing day-by-day due to the properties like high values of hardness, elastic modulus, resistance to corrosion and wear and lower amount of frictional characteristics.

Generally, the components like bearings, gears and cam–tappet subjected to rolling or rolling/sliding motion mainly fail due to contact fatigue. Rolling contact fatigue (RCF) is the mechanism of transfer of crack initiated due to the near-surface alternating stress field within the rolling-contact elements, which finally results into the removal of material. The mechanism of RCF is different from the theory of delamination of wear [1], which mainly depends on cyclic loading. The alternating stress field is either in pure rolling or in rolling/sliding conditions, depending on the amount of sliding that takes place within the rolling-contact region. However, micro-slip is unavoidable within the contact region in both pure rolling and rolling/sliding conditions. Fatigue is the predominant mode of failure in rolling element bearings; the life of bearings is governed by its RCF life [2]. The mechanism of RCF failure involves macro-pitting, micro-pitting and spalling in conventional bearings, but delamination in composite ceramics and layered coatings [3, 4]. Both conforming and non-conforming bodies are subjected to RCF. The RCF failure caused by the alternating stress field can be predicted from Hertzian contact conditions in conventional bearings and ceramic materials, but in case of layered coatings, the interpretation of stress fields needs care. It has been noticed that the protective anti-friction coating on the substrate surface of the contacting elements helps improve the fatigue life of the component [5–7]. Concurrently, it also helps enhance the tribological properties. Furthermore, the roughness of the counter body and stress distribution on the interacting surfaces plays a crucial role in defining the rolling/sliding operation conditions [8].

Therefore in the present work, the effects of different parameters like coating deposition processes, coating material properties and its thickness, use of lubricant and its additives, surface roughness and temperature on friction, wear and RCF life of coated rolling/sliding contacting elements, as regards their resistance to different mechanisms of failure have been reviewed.

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2. Surface engineering approaches to enhance life of bearing elements and their tribological properties

The final properties resulting from the substrate–coating combination, by application of different coating deposition processes, depend on the method of thermal spraying (TS, e.g., combustion flame spraying, high velocity oxy-fuel spraying (HVOF), two-wire electric arc spraying, plasma spraying, vacuum plasma spraying, etc.) and the spraying parameters (e.g., material feed rate, spray distance, number of passages, fuel gas, a potential (V), current (A), etc.). Different coating deposition processes like physical vapour deposition (PVD), chemical vapour deposition (CVD), TS, ion-beam-assisted deposition (IBAD) and reactive magnetron sputtering (RMS) are available in the market. Nowadays, processes like TS, PVD and CVD are extensively used in industries.

Hintermann [9] reported that a CVD or PVD process could be used to deposit thin and hard coating film on functional surfaces of steel. The materials used for coatings are special alloys, ceramics and cemented carbides to provide significant enhancement in the tribological properties of bearings and machine elements. Ramalingam and Zheng [10] fully justified the use of PVD process for applying thin–hard coatings on low-hardness and light alloy substrates. He underlines that such coating helps reduce the wear under boundary lubrication regime at higher stress values, in rolling/sliding contact test. Podgornik [11] concluded from his experimental study that duplex treatment comprising plasma nitriding followed by PVD had an immense effect in improving the tribological properties of contacting elements, under rolling/sliding conditions. Further, Rutherford and Hutchings [12] carried out abrasive wear tests of titanium-based alloy coatings (e.g., TiN, TiCN and TiAlN) deposited by PVD process on tool steel substrates. From their study, they observed a significant reduction in wear coefficient. In [13] the authors describe the fatigue test of thin chrome-nitride (CrN) coating deposited by PVD process onto a steel substrate. They pointed out an enhancement in fatigue resistance due to high surface residual stresses.

From the past few decades, diamond-like carbon (DLC) has been adopted as a wear-resistant material because of its low coefficient of friction (COF). Several studies, for instance [14, 15], demonstrate that the tribological behaviour of the DLC coating is strongly affected by the test environment. They find that this can be controlled by chemical reactivity of the coating, which results in production of thin films on the contacting surfaces. In their work, DLC material is deposited by plasma-assisted chemical vapour deposition (PACVD) systems. They underline that the coating films deposited under such conditions are observed to be hard, with high stress as well as a high index of refraction and low surface energy. In addition to this, the coating is characterized by very high COF in ultra-high vacuum (UHV) conditions. Further, it has been suggested [16] that low friction and wear can also be attained in UHV for DLC-coated films, by increasing the content of hydrogen (about 40 at%) with a sufficiently cross-linked carbon network, and with a considerable fraction of hydrogen unbounded to carbon.

Many attempts have been made [17–20] with the purpose of improvement in fatigue life of thermally sprayed ceramic material (tungsten carbide with different cobalt percentages, e.g., WC with 12% Co and 17% Co) deposited by high-velocity oxy-acetylene flame (HVOF) process. They concluded that a better fatigue life could be obtained by optimization of coating thickness, contact stress and lubrication regime. In [21, 22] the authors analyse that if thermally sprayed coating is followed by post-treatment like Hot Isostatic Pressing (HIP at 1200°C) or vacuum heating, the microstructure of coating improves significantly. Besides, at high temperature, diffusion takes place between coating and substrate, which results in improvement in bonding and ultimately excellent RCF performance. Berger *et al* [23] (2008) report that ceramic material (alloy of tungsten carbide–chromium–nickel WC–(W,Cr)2C–Ni) coating deposited by HVOF process exhibits a high oxidation resistance up to 900°C and can be used at high temperatures applications. Bolelli *et al* [24] fully justified the use of WC–(W,Cr)2C–Ni coating in combination with alumina in dry sliding wear test, as it depicts low wear rate and low COF. Sarma and Mayuram [25] performed RCF tests on Ni-based coating. They concluded that the coating performs satisfactorily under moderate stress levels (500–700 MPa). For improvement in the RCF life, Piao *et al* [26] deposited nickel–aluminium (Ni–Al) alloy as an interlayer between steel substrate and ferrous (Fe) alloy coating. The reported coating was deposited by plasma spraying process. Test results demonstrate that undercoating plays a vital role in the enhancement of RCF life by giving higher bond strength. In addition, undercoating helps prevent the occurrence of catastrophic delamination.

IBAD has also been found to be an effective coating deposition method, as it reduces microspalling and improves the bearing life with the usage of thin coatings. The first systematic study of titanium nitride (TiN) coating deposited by the IBAD process on M50 bearing steel was performed by Middleton *et al* [27]. He points out that this coating exhibits excellent adherence and corrosion resistance. In another study, Sansom *et al* [28] observe that IBAD process followed by PVD process produces better results. It gives good adhesion as well as formability. Several studies, for example [29, 30], have been carried out for the analysis of thin CrN coatings produced by IBAD. They observe that this process improves the RCF life remarkably as compared with three times thick CrN coating produced by closed-field unbalanced magnetron sputtering (CFUMS). Eventually, they reach the conclusion that the residual stresses developed in the coating, during the process, depend on coating thickness and are closely coupled with the microstructure.

RMS is specifically used to produce a thin and hard coating. RMS improves the bonding strength between coating and substrate. Several studies, for instance [31, 32], report that TiN coatings (up to 5 μm thick) deposited on ferrous and non-ferrous substrates by RMS provide excellent wear resistance. From metal cutting tests with the usage of RMS-coated cermet tool insert, they observed the superior performance of the tool due to improvement in the bonding between coating and substrate. In another study, Kim and Kim [33] performed an analysis of soft DLC coating deposited by RMS. They underline that in case of such coatings, COF reduces with increase in the sliding velocity and the normal load. Besides, a reduction in wear rate is observed by increasing normal load. In [34] the authors reported that the weaknesses of coatings such as brittleness and low binding strength could be improved through proper selection of ample hard phases and binders as well as proper surface preparation and process parameters.

From the different surface engineering approaches, the TS process is found to be advantageous, as it provides better diffusion and bonding within the substrate and the coating material. If it is followed by post-treatment like HIP, the microstructure of coating is found to be improved significantly. Besides, TS process can be used to produce coatings with thickness ranging from 20 μm to several mm, depending upon the type of TS process used and feedstock, over a large surface area with a higher deposition rate compared with other coating deposition processes. Moreover, any form of material can be used like wire or powder as input material. Hence the wastage of material is lower in this case, which proves it to be a more economical one, as compared with other processes.

3. Effect of coating material properties and coating thickness on friction, wear and RCF life

The coating material's elastic modulus (E_c) is useful for predicting the stress developed as well as the cracking and delamination behaviour of the coatings. A recent review of the literature on this topic finds that ratio of the elastic modulus E_c/E_s (where subscripts c and s refer to the coating and the substrate, respectively) is observed to be much higher than unity. This enhances the stress distribution at loaded contacts and creates problems such as poor coating adhesion, high flexural stresses and high residual stresses as well as coating fracture [35]. These problems can be resolved by choosing a proper combination of coating–substrate materials and an appropriate coating thickness. Hardness is another most essential property of the coating. Practically, in pure two-body abrasive wear, the wear resistance is closely related to the hardness; a rough surface has higher hardness than the counter body surface. Mostly in case of soft counter surfaces having a hardness less than 20 GPa, coating is used to improve the surface hardness. Along with the coating, Wanstrand *et al* [7] investigated the influence of the application of a thin interlayer of chromium by conducting experimental tests on thermally sprayed WC/C coating (carbide phase (WC) and the carbon (C) phase). They found that the thin chromium interlayer develops high compressive stresses and exhibits improved mechanical and tribological properties. In the case of thermally sprayed ceramic material coating (tungsten carbide with different cobalt WC–Co), Du *et al* [36] observed the problem of decarburization. From a number of trial runs for coating deposition, they claim that the temperature and feed powder velocity are the important spraying parameters and can be used to control decarburization. From their study, they conclude a closely packed microstructure, and higher values of adhesion strength and coating hardness can be obtained by decreasing and lagging the feed powder velocity and heat transfer process, respectively.

Experiments on carbon nitride (CN_x) coating were performed by Bakoglidis *et al* [37, 38], who deposited by employing high power impulse magnetron sputtering (HiPIMS) with a thin tungsten (W) adhesion layer. The CN_x coating exhibits high hardness, high modulus of elasticity and high bonding strength. From the wear test results, they point out that CN_x coating with W interlayer performs better and gives rise to mild wear and high fatigue life. Bayon *et al* [39] examined the tribological performance of Cr–Cr and CrN–ZrCN multilayer coatings applied by PVD process on nitrided steel used for gearing applications. The test results depict that Cr–CrN coating significantly improves the wear resistance compared with the CrN–ZrCN and nitrided substrate. The microscopic study shows that Cr–CrN coating protects the micro-pitting of the substrate surface and prevents the fatigue failure of uncoated discs.

As a more recent evidence, Wang *et al* [40] propose that hot-pressed (HIP) silicon nitride (Si_3N_4) material can be used as a hybrid steel–ceramic bearing material. This material exhibits higher values of hardness and modulus of elasticity in comparison with steel. These properties help reduce the dynamic loading at ball–raceway contacts. The authors report that such properties are found to be essential in high-speed applications like gas turbine engines and machine tool spindles, and result in improvement in the RCF life. Kataria *et al* [41] fully justified the use of silicon nitride (Si_3N_4) bearings in severe tribological conditions as well as at-large temperature gradient, high speed and UHV applications. They suggest that this material is also suitable for short periods of oil-off operation in aircraft engines and has better corrosion resistance as well as ability to perform in the contaminated environment. Several studies, for instance [42–44], have been performed on RCF testing of cermet coatings (e.g., Fe–Cr and CrC–NiCr). The test result indicates that, with the increase in contact stress, the RCF life decreases; at the same instant, failure mode of the coatings changes from abrasion and spalling to delamination. In line with this, the macroscopic study shows the failure modes of coatings linked with micro-defects, the bond strength of the coatings and orthogonal shear stress (OSS) developed within the coatings. Some preliminary work on the performance of soft coatings was carried out several years ago. The first systematic study on soft coatings like molybdenum (Mo) and Al-bronze was carried out by Akdogan *et al* [45]. They report that Mo has low hardness and low elastic modulus, and exhibits higher surface failure life in comparison with Al-bronze coatings under the condition of pure rolling/sliding. In addition to this, with an increase in load, the flaking failure life decreases for Al-bronze whereas the slip ratio increases, and the Al-bronze coating produces extreme wear and rapid surface failures.

Ahmed and Hadfield [46, 47] investigated the performance of WC–15%Co, and thermally sprayed Al_2O_3 coating on M-50 bearing steel substrate under fully wet condition. The RCF tests results reveal that WC–15%Co coating has more fatigue resistance than Al_2O_3, due to high elastic modulus and high hardness than those of Al_2O_3. Edge cracking and delamination were found to be the mechanism of failure for WC–15%Co while Al_2O_3 surface failed due to de-bonding of the coating from the metallic substrate. Podgornik *et al* [48] fully justified that coatings with relatively low elastic modulus and low hardness wear out gradually.

In [49] authors describe fabrication and testing of roller and ball bearings coated by electroless nickel–phosphorous (Ni–P) alloy plating, in contact with a sulphureted counter roller in pure rolling lubricated contact condition. They point out that lives of both the Ni–P plated and sulphureted roller and ball bearing improve remarkably as compared with that of non-coated rollers. Another interesting observation finds that in case of a plated roller whose elastic modulus is lower than that of the substrate, the contact pressure and subsurface stresses are lower than that of a non-coated roller. They underline that this reduction is due to conformity between the surfaces, by the wear of the plated layer. Kang *et al* [50] deposited Ni–Al coatings on the tempered AISI1045 steel rollers by supersonic plasma spraying method. Before application of the coating, substrate surface was sand blasted and preheated up to 200°C. They analysed the performance of the coating using a novel RCF–wear multifunctional test machine. The experimental results show that, in case of pure rolling condition, the coating fails, with delamination, spalling and surface abrasion. The delamination of coatings takes place due to subsurface cracking, which is related to the maximum shear stress. The micropitting of the coating leads to surface abrasion failure. Moreover, under rolling–sliding contact condition, failure of the coating is observed due to delamination and surface abrasion. Besides, increase in the frequency of delamination failure is observed with increase in the slip ratio.

Nakajima *et al* [51] conducted the durability test on the thermally sprayed cermet coating (WC–Cr–Ni) using a two-roller test-rig at different roller speeds. From the test results, they reach a conclusion that flaking occurs when the coated roller has slow speed. At the same time, the coating thickness is directly related to the flaking life. The soft or hard nature of the substrate has a remarkable influence on the durability of the coating [52]. Moreover, in the case of induction hardened steel (IHS) substrate, flaking occurs typically in the coating. However, for thermally refined steel (TRS) substrate, flaking occurs along the interface of coating–substrate or just below the coating. Iwai *et al* [53] studied the performance of single-layered TiN and a multilayered (TiN–NbN, TiN–TaN, TiN–CrN) coating. They claim to have demonstrated that single-layered coatings with coarse lamellae of TiN–TiAlN have a higher erosion resistance than the thin multilayered coatings. Mao *et al* [54] carried out experimental tests on untreated, TiN-coated, plasma-nitrided and duplex-treated (i.e. plasma-nitrided plus TiN-coated) steel gears. In order to analyse the performance of the coatings, test parameters such as speed load and distance are kept constant. Among all these coatings, duplex-coated gears exhibit excellent endurance life due to synergetic effect of both the coatings. The improved interface properties help improve the endurance life. As per the comparison of wear life, plasma nitriding remains at the second position, which is followed by TiN-coated gears. In case of plasma-nitrided steel, gradual decrease in the hardness was found from the surface to the substrate, which led to reduction of wear resistance. However, in case of TiN-coated steel gear, poor performance was observed due to variation in the hardness between the coating and substrate. The TiN coating fails to adhere on the untreated steel, due to which cracks are initiated under TiN layer and then breakdown of the coating takes place. Further, PalDey and Deevi [55] fully justified that (Ti, Al)N coatings perform very well in comparison with the commercially available other Ti-based coatings. They suggest that such coatings suit for applications like dry machining, high-speed machining, coating on extrusion dies as well as die-casting dies.

Erdemir and Hochman [56] and Erdemir [57] analysed the effects of hard material coatings (e.g., CrC, TiC and TiN) on the RCF performance on different bearing steel materials (i.e., 440-C, M-50, BG-42, etc.). Coatings of different thicknesses (i.e., 0.2–2.4 μm) were deposited on steel substrates by CVD, magnetron sputtering and ion plating. Fatigue tests were carried at two different stress levels: 4.04 and 5.42 GPa. The experimental result shows that the thickness of the TiN coating has a significant influence on RCF life. The thin TiN coatings (< 1-μm thick) resulted in enhanced L10 and L50 fatigue lives of the base steels. A few thick coatings tested at 4.04 GPa also performed well. The L10 and L50 fatigue lives of thick (above 2 μm) TiN-coated steels reduce due to abrasive third body wear caused by the delaminated and crushed TiN particles. Chang *et al* [58, 59] carried out the RCF tests of TiN-coated rollers at a 2.3 GPa contact pressure using a twin-disk rolling-contact test rig. The primary focus of the study was to analyse the influence of TiN coating thickness (ranging from 0.25 to 5 μm) on RCF life of rollers. From their research, it was observed that 0.25-μm thick TiN coatings provide the best fatigue resistance. The thick coatings suffered larger initial spans. Overall, this study shows that the coating thickness greatly affects the RCF performance of bearing steel substrates. A thin hard coating (i.e., 0.2–1 μm thick) helps improve the fatigue life. Thicker coatings most often delaminate and may shorten the life. Several studies, for example [5, 17, 18], conducted to analyse the effect of variation in the coating thickness of thermally sprayed (HVOF) WC–12% Co coating, coated on 440-C steel substrate in combination with different lubricants and at the same contact load, are reviewed and shown in table 1.

In general, these results would seem to suggest that modulus of elasticity and hardness are the two properties of the coating of primary importance useful to predict fatigue and wear resistance. Along with these, fracture toughness, corrosion resistance, fatigue strength and adhesion are the secondary important properties, which help improve the performance of the coating. Despite these material properties, the thickness of the coating also plays a significant role in case of improvement of RCF life. For lubricated contacts, the pressure and film thickness distributions are closely related to the coating thickness. Hence, optimum coating thickness is required to improve the performance of the coating.

4. Effect of lubricant and its additives on friction, wear and RCF life

Most of the components of rotary and reciprocating machines work under lubricated conditions, where the lubricant plays a vital role in reducing the friction. Specifically, under boundary as well as mixed lubrication regimes, chemical reactions between oil additives, the oxygen content in the environment and metal surfaces will decide the tribological behaviour of the contacts. In their seminal work, Rico *et al* [60] carried out experiments with different samples of mineral and synthetic oils for rolling contacts. From the results, they underlined that lubricants exhibit an improvement in the RCF life of mechanical components. Besides, oils of the same family having higher viscosity provide enhanced RCF life. Several authors, for instance [61, 62], performed durability test of a DLC coating (15 at% hydrogen) under rolling–sliding contact with the counter body as uncoated steel (0.5 slide to roll ratio). The tests were carried out by employing different lubricants using additives like zinc-dialkyl-dithiophosphate (ZDDP) and friction modifiers (FMs) like Moly Dimer (MD) and Moly Trimer (MT). The authors come to the conclusion that the ZDDP additives reduce the wear remarkably to low levels, while the MT additives have only minimal influence on wear; however, use of MD additive increases the wear.

More recent evidence by Bjorling *et al* [63] shows that when a DLC coating has been smeared on one of the surfaces, a significant decrease in COF has been observed in full film regime. Also, when both surfaces are coated again, COF has been reduced compared with previous values. In another study, Kalin *et al* [64] pointed out that the chemical reactivity of DLC coatings along with the present additives in the lubricant was poor and difficult to optimize. Qi *et al* [65] carried out a systematic study on the tribological behaviour of DLC-coated surfaces lubricated with different lubricants under various conditions like with and without sand-dust particles. The lubricants used for experimentation include Polyalphaolefine (PAO), Perfluoropolyether (PFPE), Silicone oil (SO), Hexafluorophosphate (IL) and Multiply-alkylated cyclopentane (MAC). They studied the effect of frequency, load and sand-dust particles on the tribological performance of the DLC coating. Their study reveals that coatings lubricated with solid–liquid lubricants including SO and IL demonstrate outstanding anti-friction performance but exhibit poor wear-resistance. There is still considerable ambiguity regarding the chemical reactivity of the DLC coating. This led authors of [66, 67] to investigate the effect of replacement of the chemically reactive lubricant with a physically based additive. They observed a 30% decrease in friction with the coating–lubricant combination, but a 50% decrease in friction with the coating–lubricant–MoS_2 additive combination, in comparison with uncoated steel surface–lubricant combination. Many attempts have been made [68, 69] for the betterment of the tribological properties of DLC coatings with the usage of extreme pressure (EP) and anti-wear (AW) additives. Their study highlights that DLC coating provides 25% superior

Table 1. Effect of variation in coating thickness of thermally sprayed (HVOF) WC–12%Co coating on 440-C steel substrate.

Sl. No.	Coating thickness (μm)	Contact load (N)	Contact stress (GPa)	Fatigue life (million rev.)	Lubricant	References
1	50	380	2.7	1	Hitec 174	[5]
2	150	380	2.7	55	Hitec 174	[5]
3	235	380	2.7	70	Exxon-2389	[17, 18]
4	250	380	2.7	70	Hitec 174	[5]

Table 2. Effect of different lubricants with additives on COF and Wear volume [48].

Sl. No.	Contact pair	PAO	PAO + EP	PAO + AW	GL4
COF for different contact pair at 700 N load					
1	Steel/steel	0.078	0.072	0.073	0.079
2	DLC/DLC	0.078	0.058	0.054	0.064
3	DLC/Steel	0.08	0.05	0.052	0.065
Wear volume $\times 10^{-3}$ (mm^3/mm) for different contact pair at 700 N load					
1	Steel/steel	0.65	0.6	0.5	0.55
2	DLC/DLC	0.83	0.76	0.74	0.78
3	DLC/Steel	0.55	0.42	0.42	0.56

PAO—Polyalphaolefine oil

PAO + EP—Polyalphaolefine base oil with extreme pressure additives

PAO + EP—Polyalphaolefine base oil with anti-wear additives

GL4—Fully formulated gearbox oil

frictional and wear properties with the use of PAO oil suspended with EP and AW additives, as compared with only PAO as a base oil. The COF and wear volume of the different contacting pairs of materials in combination with different lubricants are reviewed and listed in table 2.

Similar to the previous study of DLC coating with lubricant and different additives, several studies, for instance [70–72], were performed on the combination of WC/C with lubricant and various additives. They highlight that the usage of EP and AW additives reduces the steady state friction drastically. Besides, these additives tend to intensify coating wear rate due to a chemical reaction, which results in a polishing type of wear. The COF and wear volume of different contact pair of materials in combination with different lubricants are reviewed and listed in table 3.

More recent evidence [73] proposes that WC-doped DLC coatings wear out at a faster rate compared with TiC-doped DLC coatings in the presence of lubricants with sulphur-based additives. They point out that this happens because of the higher reactivity of sulphur (S) with tungsten (W) as compared with Ti. This leads to the production of dichalcogenide species (i.e., formation of thin films), which helps reduce the friction. Ronkainen *et al* [74] in 1998 investigated experimentally the tribological performance of hydrogen-free amorphous carbon (a-C) and hydrogenated amorphous carbon (a-C:H) coatings in dry 50% relative humidity (RH), water-lubricated and oil-lubricated sliding conditions. They point out that COF in case of hydrogen-free amorphous carbon and hydrogenated amorphous carbon films can be reduced by 10–40% in boundary lubrication regime as compared with dry sliding contacts. They conclude that hydrogen-free amorphous carbon film offers outstanding wear resistance in dry and aqueous as well as oil-lubricated conditions. The hydrogenated amorphous carbon film exhibits good self-lubricating properties, but it is subjected to severe wear in aqueous conditions. They suggest that Ti-alloying can enhance the performance of hydrogenated amorphous carbon film. Vanhulsel *et al* [75] carried out an experimental analysis of DLC- and MoS_2-coated angular contact ball bearings in air and vacuum environment. Their study reveals that in air, comparatively higher torques are generated and also lower amount of coating wear takes place for both types of coatings. They

Table 3. Effect of different lubricants with additives on COF and Wear volume [71, 72].

Sl. No.	Contact pair	PAO	PAO + EP	PAO + AW	GL4
Steady-state friction at 4 GPa contact pressure, determined after 1000 cycles					
1	Steel/steel	0.078	0.07	0.072	0.075
2	WC/C-WC/C	0.079	0.06	0.06	0.072
3	Steel/WC/C	0.081	0.05	0.052	0.07
Wear volume per unit length $\times 10^{-3}$ (mm^3/mm) after 30000 cycles at 4 GPa					
1	Steel/steel	1	0.9	0.88	0.88
2	WC/C-WC/C	0.93	0.75	0.75	0.82
3	Steel/WC/C	0.83	0.6	0.6	0.75

PAO—Polyalphaolefine oil

PAO + EP—Polyalphaolefine base oil with extreme pressure additives

PAO + EP—Polyalphaolefine base oil with anti-wear additives

GL4—Fully formulated gearbox oil

conclude that DLC-coated bearings withstand higher torques level when tested for in-air ground without too much interruption of the succeeding in-space performance.

Michalczewski *et al* [76] analysed the performance of four different coatings in combination with different lubricants. The TiN and CrN coatings were deposited by arc-vacuum PVD process while hydrogenated amorphous carbon doped with tungsten (W) and MoS_2–Ti coating were deposited by RMS. Different lubricants include synthetic oil, mineral oil and commercial automotive gear oil. Scuffing tests were performed using a four-ball tester machine. They conclude that hydrogenated amorphous carbon doped with tungsten (W) coating has better scuffing and pitting resistance, which suits for rolling/sliding contact applications. Hintermann *et al* [77] carried out experimentation by applying hard material coatings (e.g., TiC, TiN and Ti(C,N)) onto deep ball bearing rings made of steel material and balls with cemented carbide material by the application of CVD process. The tests were performed under different load, speed and environmental conditions. They find that coated bearing provides high wear resistance as compared with conventional one, which leads to enhancement in operating life of the bearing. In [78] the authors performed a friction test of a NiCrBSi alloy coating produced by laser cladding. PAO oil was used as a lubricant with suspended CuO nanoparticles. They outline that as compared with base oil, nanoparticle-suspended oil exhibits less friction at a low load, due to fewer asperities interaction. Several studies, for example [79, 80], report that organic FMs (like phosphorus compound, alcohol, carboxylate, amine, amide, imide, borate, ionic liquid, MoS_2) help enhance the tribological properties by the development of protective thin films. Besides, usage of nanoparticles based on carbon compound, metal, metal-sulphide, metal-oxide, metal-carbonate, metal-borate and SiO_2 acts as extremely effective FMs and helps reduce the friction significantly.

Wong *et al* [81] simulated wheel–rail rolling–sliding contact, coated with molybdenum disulphide (MoS_2) and tungsten disulphide (WS_2) coating. From their study, they found that both metal disulphides show reduced decomposition temperature under sliding/rolling conditions. They analyse that high pressure and micro-slip motion in the contact zone have a remarkable effect on the decomposition pathways for both the coatings. Arias-Cuevas *et al* [82] simulate the wheel–rail contact using a twin-disk roller rig to analyse the performance of two different water-based FMs, FMA and FMB, in dry and wet contacts. From their study, they find that FMA has a long life, due to the robust matrix established within the polymeric components and the solid particles. Steadfast adherence of FMA to the disk surfaces is observed due to the polymeric components. However, due to poor bonding within solid particles and gelling agent in case of FMB, the solid particles are removed from the disk surfaces. Also, in the presence of water, the durability of FMB has been decreased. Ma *et al* [83] carry out wear tests using a rolling–sliding apparatus to analyse the influence of slip ratio on the RCF life and wear of rail–wheel contact under the dry condition. From their study, they observe that rail–wheel rollers are subjected to different damage mechanisms with the variation in the slip ratio. With an increase in the slip ratio the mechanism of wear of rollers changes from oxidation and adhesion to severe fatigue and spalling.

The evidence from this study implies that, to minimize or to avoid direct contacts between rolling–sliding elements, a thin film of lubricant is required to be maintained. Many researchers have experimented with different kinds of lubricants to enhance the tribological performance of the system. From the collected data, the PAO synthetic oil is found to be a better lubricant in boundary as well as mixed lubrication regime. Besides, PAO mixed with sulphur-based EP additives (PAO + EP) and PAO mixed with ZDDP-based AW additives (PAO + AW) help improve the performance of the system in severe conditions. In case of dry/lubricated contacts DLC, MoS_2 and WS_2 are the main soft coatings, which have been used mostly for improving the tribological performance.

5. Effect of surface roughness on friction, wear and coating durability

Surface roughness produces small-scale contact stress spikes, which results in near-surface RCF initiation. When the surface roughness is smaller with one order magnitude of the coating thickness, frictional effects come into the picture. An improvement in the quality of surface finish with the application of coating was noticed by Polonsky *et al* [84]. Besides, the substrate also protected effectively from the wear. To study the surface kinematics and effects of orientation of the asperities, Kaneta [85] developed the micro-EHL model. Their study reveals that the EHL film gets broken with asperity interactions and the deformation of each asperity depends upon the surface kinematics as well as asperity orientation. Eventually, they point out that microscopic deformation leads to surface failures. More recent evidence [86] proposes that in case of DLC coating doped with WC, when the surface roughness is low, the durability of the coating is found to be higher under boundary lubrication regime. Further, Krantz *et al* [87] extended the study and carried out the fatigue testing of uncoated and coated gears by accelerated life tests. The gears were case-carburized, heat treated and coated with Me-DLC coating. They outlined that the RCF life of the coated gears improved because of wear resistance offered by the coating. Also, the change in the surface topography of the tooth while running (due to a polishing type of wear) plays a vital role for improvement of the RCF life. Unfortunately, the carburized and heat-treated steel substrate has poor scuffing resistance. To improve the scuffing resistance, instead of carburising and heat-treated steel,

Table 4. Effect of surface roughness on RCF life and coating failure [90].

Roller D condition prior to spraying	Rollers	Hardness Hv	Thickness (μm)	Roughness R_y (μm) Before	After	Hertz stress (GPa)	Slip ratio (s %)	COF (μ)	Life in (million rev)	Surface damage
Axially ground substrate	F	759		4	2	0.8	−14.8	0.062	20	F: No
	D(TRS)	1111/327	52	0.2	1			0.037		D: No
Blasted substrate	F	786		4	6	0.8	−14.8	0.067	11.97	F: No
	D(TRS)	1090/330	54	0.2	3			0.035		D: Flaking
Axially ground substrate	F	816		3	2	1.4	−28	0.05	20	F: No
	D(IHS)	1131/684	61	0.1	1			0.032		D: No
Circumferentially ground substrate	F	807		5	2	1.4	−28	0.051	20	F: No
	D(IHS)	1001/669	58	0.1	2			0.039		D: Flaking

F roller without coating carburized and hardened chromium molybdenum steel (SCM415)

D roller with WC-Cr-Ni cermet coating, substrate material-induction hardened steel (IHS) /thermally refined steel (TRS) (S45C)

In table Roller D mentioned with coating hardness/substrate hardness

Alanou *et al* [88] proposed a triple process combination of nitriding, super-finishing and DLC coating. They observed that this combination greatly improves the scuffing resistance. Further, to analyse the effect of soft or hard nature of substrate on fatigue failure of coating, authors of [89] carried out fatigue test of cermet coating (WC–Cr–Ni) applied on IHS substrate and TRS substrate. From their analysis, they concluded that the flaking life of WC-cermet-coated roller was being enhanced by increasing coating thickness. Moreover, the IHS-substrate-coated roller exhibits a longer life in comparison with the TRS substrate. Besides, the pre-treatment process like grinding helps control the flaking of TRS substrate, by grinding the substrate axially, whereas durability of coated roller gets reduced due to blasting or circumferential grinding of the substrate. For understanding, the numerical data are reviewed and tabulated as shown in table 4.

Carvalho *et al* [90] reported a similar kind of study for TiN-coated rings machined by pre-treatments like polishing and grinding. They claim that at low-stress levels the fatigue durability is remarkably affected due to pre-treatment and final roughness on the surface of substrate material. They describe that a polished and smoother surface gives out a better fatigue life. Moreover, at a high contact stress level, they observe that pre-treatment and surface roughness result into minimal effect on RCF life. The effect of different surface roughness values obtained by polishing and grinding for TiN-coated specimens on RCF life at low-stress levels is reviewed and listed in table 5.

As a more recent evidence, Ronkainen *et al* [91] performed an elasto-plastic analysis to investigate the influence of surface roughness on the durability of the coating. They point out that rough surface helps improve the durability of coating as compared with the smooth surface, especially when the thin coating is applied in case of a less hard substrate such as TRS. Several studies, for instance [92, 93], investigated the effect of pre-treatment like grinding or super-finishing on the scuffing resistance of the coating. They conclude that application of the hard coating onto the ground disks remarkably improves the scuffing resistance as well as the frictional characteristics; however, in the case of super-finished discs, the durability of the coating gets lowered. Authors of [94] performed wear and friction test on different substrate materials like bearing steel, hot-pressed silicon nitride (Si_3N_4) and titanium alloy bearing coated with sputtered MoS_2 films. Their study reveals that the friction and wear vary significantly with the substrate material and surface roughness of the substrate.

Table 5. Effect of surface roughness on RCF life [90].

Sl. No.	Coating Thickness (μm)	Contact stress (GPa)	Roughness Polishing (μm)	Roughness Polishing (μm)	Roughness Grinding (μm)
TiN coating deposited on tool steel substrate by PVD					
			0.09	0.2	0.12
			Life in million rev.		
1	2–5	3.5	0.2	0.02	0.12
2		4.6	0.28	0.03	0.09
3		5.1	1.33	0.34	0.14

This was observed due to the softness of the MoS_2 films, and variation in friction in case of steel and Ti alloy substrates with an increase in surface roughness.

The findings of this study indicate that the rough substrate surface helps to adhere the coating very well and it results in improvement in the durability of the coating. However, a higher surface roughness of the coating results in abrasive wear. Moreover, in the case of hard coating application, pre-treatment like grinding helps improve the scuffing resistance. Hence, as per the need of application and nature of the coating, there is a necessity to maintain optimum surface roughness for improvement in the performance of the coating.

6. Effect of thermal aspect on friction and wear

The performance study of the coating up till now has been carried out on the assumption of isothermal conditions. In the past the analysis was carried out by taking into account only the effect of coating elastic modulus as well as coating thickness on fluid film thickness and pressure distribution in EHL contacts. In 2015, Bobzin *et al* [95, 96] carried out the analysis of different DLC coatings deposited on the steel substrate. The authors find that these coatings produce a significant reduction in COF under boundary, mixed as well as under EHL regimes. They hypothesize that DLC coatings act as a thermal barrier coating because of their favourable thermo-physical properties, i.e., thermal conductivity and specific heat capacity in comparison with steel. The Bobzin hypothesis seems to be well-grounded in the flash temperature theory, pioneered by scientist Blok, which depicts that with the increase in the contact temperature in the lubrication gap, the shear resistance of the lubricant changes. Besides, the insulating property of the coating tends to reduce the mass temperature of the disk since the mass temperature principally predicts the fluid film thickness. Eventually, at lower mass temperatures, the higher lubricant film thickness occurs. Further, Bjorling *et al* [97] fully justified the Bobzin hypothesis by performing the experimental and numerical analysis of the DLC coating. The results obtained by both methods are found to be in close agreement. In the developed numerical model, authors ignore accumulated heat, chemical reactivity and surface interaction effects. Hence, they come to the conclusion that the decrease in friction for the obtained results is because of the thermal effects only.

Taken together, these results suggest that DLC coatings act as a thermal barrier coating because of their favourable thermo-physical properties, i.e., thermal conductivity and specific heat capacity, in comparison with steel. From the thermal aspect point of view, the coating material that possesses low thermal conductivity and low specific heat capacity helps improve the tribological performance of the contacting surfaces.

7. Surface coating effect on friction and wear while considering surface texturing

Surface texturing is one of the most popular surface preparation techniques due to its flexibility and high accuracy. Several experimental studies, for instance [98, 99], reported that the performance ability of textured surface is influenced by geometrical properties and bearing components operating conditions. In hydrodynamic and mixed lubrication regimes, it has been observed that surface textures act as reservoirs for lubricant film, which helps in producing additional micro-hydrodynamic lift effect. Finally, this results in a separation of the contacting surfaces. In 2015, Ibatan *et al* [100] highlighted that surface texturing helps trap wear debris into the micro-cavity, which further reduces the abrasive wear taking place due to ploughing, especially in boundary lubrication regimes. It gives several benefits such as a reduction in friction and sustainability at higher load carrying capacity, which mainly varies along with texture geometry, texture shape, texture pattern and the types of contact. Sudeep *et al* [101] reported that the combination of surface texturing and surface treatments such as surface coating proved to be beneficial in terms of improved tribological properties under severe operating conditions subjected to rolling/sliding motion. Authors of [102] fabricated micro-reservoirs with a focused UV laser beam onto the surface of harder TiCN coatings, MoS_2 and graphite-based solid lubricants smeared by sputtering and burnishing onto the laser-textured surfaces. The test results indicate improvement in the solid lubricants life on dimpled surfaces compared with the untextured TiCN coating surface. They point out that the micro-reservoirs produced due to laser operation help supply lubricant continuously in humid air and dry nitrogen environment.

In 2017, Lu *et al* [103] performed experimental analysis to investigate the effect of texture shape as well as texture geometry onto the lubricated–coated contacts. They find that a converging and diverging feature of the textured surface significantly influences the friction behaviour of the contacting surfaces across all lubrication regimes. Besides, a shorter contact length is advantageous for local friction reduction. Eventually, the study reveals that lubrication effect can be enhanced using a converging shape dimple that is partially covered by the contact area. Authors of [104] further extended the research and carried out an experimental study to observe the effect on COF and wear rates of the surfaces with and without dimples for metal-to-metal and metal-to-plastic contacts. They highlighted that surface texturing creates a positive impact on the COF and wear rates of the textured surfaces. Ramesh *et al* [105] carry out a similar kind of study and report that in case of hydrodynamic lubricated sliding contacts, the textured surfaces exhibit friction near about 80% lower as compared with the non-textured surfaces. Chouquet, an authority on the combined study of test surface-texturing–DLC coating, affirms that texturing improves tribological behaviour under lubricated sliding conditions and adapted texture geometry and helps reduce COF significantly at low sliding speeds [106]. Further, Amanov *et al* [107] studied the tribological properties of the textured and untextured Si–DLC coatings deposited onto the bearing steel surface using a CVD system. Their study reveals that the textured Si–DLC coating exhibits enhanced tribological properties in comparison with an untextured coating. As a more recent evidence, Da Silva *et al* [108] carried out analysis on coated square cemented carbide tool inserts with three layers of TiCN–Al_2O_3–TiN coatings. Their study mainly focused on the effect of texture geometry and texture pattern. For this, the specimens have been textured in parallel and perpendicular patterns to the direction of the chip movement. Micro-abrasion and turning tests have been carried out on both textured and non-textured conventional tools. Their study reveals that in the case of turning tests, textured tool insert has a significant increase in tool life, due to a supply of cutting fluid at higher contact temperatures. The only limitation observed in the case of micro-abrasion tests is that coating wear rate increases significantly due to the decrease in coating hardness resulting due to laser texturing.

Overall, this study implies that texturing of a tool rake surface results into enhanced tool life. Textured pattern along with grooves having a perpendicular orientation to the chip movement provides a significant increase in tool life as compared with parallel grooves. The LST technique with a combination of the Si–DLC coating also exhibits a significant reduction in COF and wear volume as compared with non-textured samples. Eventually, application of surface texturing with the combination of coating serves two purposes. First, it permits storage of solid lubricants and second, it provides a multifold increase in the wear life of the contacting elements.

8. Numerical analysis of coated surfaces

Lijesh and Amirthagadeswaran [109] carried out a numerical analysis of a substrate–interlayer–coating combination using FEM. The result shows that an interlayer acts as a stress reducer within the coating and the substrate material. Their model predicts that in the case of thin coating and high elastic modulus, high Von-Mises stresses develop. From their study, they come to the conclusion that for proper selection of a substrate–interlayer–coating combination, optimization technique proves to be an excellent one. Liu *et al* [110, 111] further extended the numerical analysis to study the effects of coating on film thickness at different conditions of speed, load, rheological model and pressure–viscosity behaviour. They observed a distinction between the behaviour of a stiff and compliant coating. A stiff coating increases the COF, while a compliant coating helps reduce the viscous friction; however, the effect of coating on friction becomes smaller in case of high values of speed or load. Several studies, for instance [112–114], developed a nonlinear viscous fluid model to carry out transient micro-EHL analysis of line contact coated specimens. They pointed out that the lower value of elastic modulus of the coating material increases the conjunction width of the lubricant and reduces the pressure distribution as well as the pressure spike and vice-versa in case of a higher value of elastic modulus coatings as shown in figure 1.

Liu *et al* [115, 116] developed an isothermal EHL model based on a point-contact to predict the influence of a change in elastic modulus and thickness of the coating. They noticed that minimum lubricant film thickness is a function

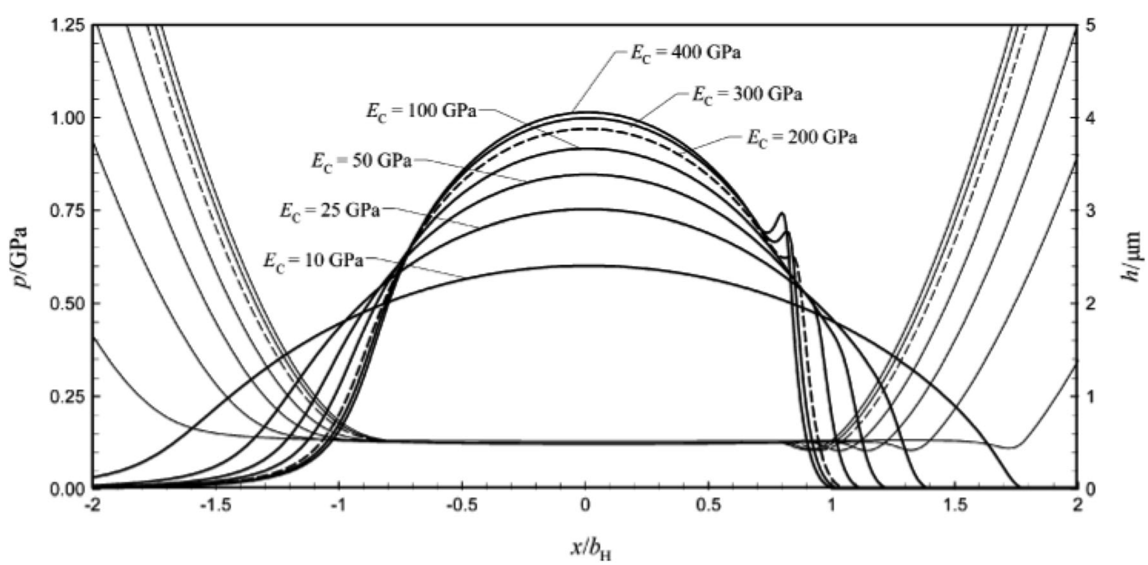

Figure 1. Effect of variation in elastic modulus (E_c) of the coating material on film shapes and pressure distributions (at constant coating thickness t_c = 20 μm) (Refer fig.6 from [112]).

of coating material thickness and its modulus of elasticity for a broad range of working conditions. A similar kind of study is conducted by Wang *et al* [117], who observe that in case of stiff coatings, the coating thickness is directly related to the compressive stress while indirectly related to the tensile stress. Besides, a stiff coating enhances the Von-Mises stresses at the interface of coating and substrate. Chu *et al* [118] reported a new method to carry out analysis of transversely isotropic coated EHL contact model using FEA. He has compared the obtained elastic modulus matrix with the elastic modulus matrix of an anisotropic material to estimate the appropriate range of coating thickness under the same relative error. Eventually, he concludes that the pressure distribution tends to increase gradually and to concentrate towards the centre with an increase in longitudinal elastic modulus. Yu *et al* [119] developed a TEHL model for a coated cam–tappet contact. Their numerical model predicts that thermal properties of the coatings have minimal effect on the pressure and film thickness distribution, but a significant influence on the temperature distribution as compared with an uncoated cam–tappet contact. They concluded that a soft coating with low thermal inertia has the greatest ability to decrease the friction loss. The effect of the coating thickness on the frictional loss with different thermal inertias is shown in figure 2 (see figure 9 of [120]). The temperature distribution with low, regular and high thermal inertia in coated TEHD circular contacts along the centreline of the contact keeping constant SSR and coating thickness is shown in figure 3 (see figure 10 of [120]). Habchi [120–122] contributed a lot in the area of thermal aspect, related to coated rolling/sliding contacts. He has carried out a FEM analysis with TEHD model developed for coated circular contacts. He underlines that the central pressure and the pressure spike height increase along with coating elastic modulus, whereas the contacts width is found to be reduced. He found that this effect is accelerated with an increase in the coating thickness. Eventually, he concluded that surface coatings with low thermal inertia act as an insulator, which leads to an increase in the localized lubricant temperature at the centre of the contact. Besides, a significant decrease in friction has been achieved with constant film thickness. Recently Lohner *et al* [123] developed a THEL model for highly loaded rolling/sliding contacts considering non-Newtonian fluid behaviour. He concludes that lubricant's viscosity, density, rheological behaviour and oxidation stability, as well as tribofilm formation, remarkably depend upon EHL contact temperature.

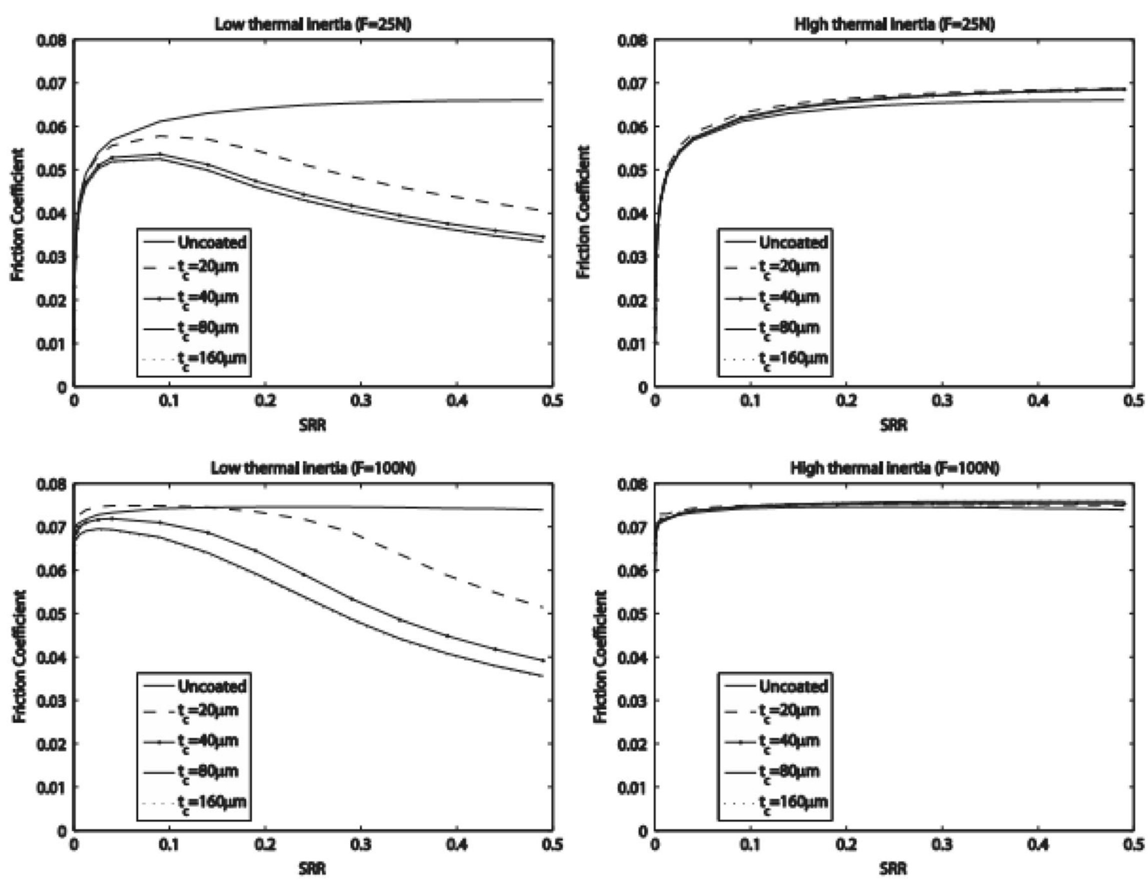

Figure 2. Effect of variation in coating thickness on COF with low and high thermal inertia (at different slide to roll ratio (SRR)) (Refer fig. 9 from [120]).

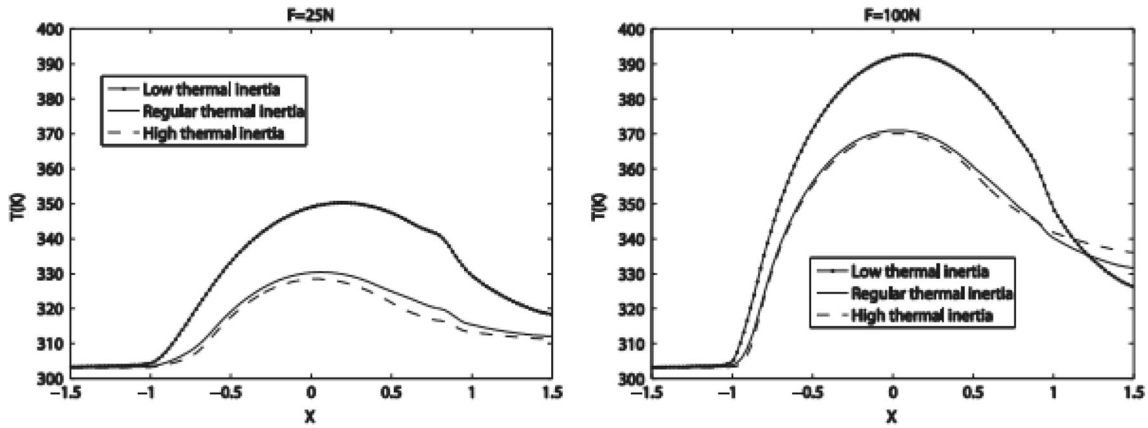

Figure 3. Temperature distribution along the centerline of the coated circular contact at the mid-layer of the lubricant film, (for low, regular and high thermal inertia materials at F = 25 N and F = 100 N) (Refer fig. 10 from [120]).

From the overall numerical study, it has been observed that elastic modulus and thickness of the coating significantly affect the pressure distribution and film thickness of the lubricant. They also cause development of high Von-Mises stresses at the interface of the coating. The numerical study illustrated that lubricant's viscosity, density, rheological behaviour and oxidation stability as well as tribofilm formation remarkably depend upon EHL contact temperature.

9. Summary

This review has briefly summarized the extensive study of the effect of different parameters like coating deposition processes, coating material properties and its thickness, lubricant and its additives, surface roughness and temperature on RCF life and tribological properties of coated rolling contacts and sliding contacts.

- The surface engineering approach clearly shows that TS process, followed by HIP, provides better diffusion and bonding due to high temperature. This helps improve the RCF life by controlling the residual compressive stresses.
- Much work has been done on hard coating materials as compared with soft coatings. In hard coatings, the maximum amount of work is done on tungsten carbide with variation in cobalt percentage (e.g., WC–12% Co, WC–15% Co and WC–17% Co) and titanium-based coatings (e.g., TiC and TiN). These hard coatings have shown a significant improvement in wear resistance and RCF life of bearing steel. A limited amount of work is done on soft coatings like DLC, MOS_2 and WS_2. Soft coatings are mainly helpful in reducing friction and wear between the interacting surfaces, and further attention is needed in this direction to study the different soft coating materials.
- Modulus of elasticity and hardness are the inherent material properties of the coating material that help improve RCF life as well as wear resistance of the contacting surfaces. The evidence from the literature shows that the thickness of the coating also helps improve the RCF life of the contacting surfaces. The experimental investigations were carried out using a certain range of coating thickness due to practical limitations. This fails to address an optimum coating thickness value. It can be interesting to find the optimum coating thickness through numerical as well as experimental investigations that will improve the RCF life of the contacting surfaces.
- The viscosity of the lubricant plays a vital role in the improvement of the RCF life and tribological properties of coated mechanical components. The study shows that the oil having higher viscosity provides higher RCF life but the literature does not clearly mention the optimum value of viscosity of the lubricant. Lower viscosity may lead to the problem of direct contact between the surfaces and higher viscosity may lead to fluidity problem. Therefore, another future research direction is to carry out both experimental and numerical study to find the optimum value of viscosity that will improve both RCF life and tribological properties.
- The surface topography study indicates that the rough surface of the substrate helps improve the durability of coating, especially in case of a thin hard coating. The surface finishing processes (e.g., polishing, grinding and blasting) lead to different surface roughness values. The optimum range of surface roughness values where the durability of surface coating improves is not yet known. The roughness can be random or determined. If the roughness is determined, e.g., surface texturing, further work needs to be carried out on the texture attributes (e.g., shape, size and orientation) that helps improve the RCF life and tribological properties.

- As already discussed, the viscosity of the lubricant plays a vital role in the improvement of the RCF life and tribological properties of coated mechanical components. The study carried out in the field of coated rolling/sliding contacts was purely based on the assumption of an isothermal process, which fails to take into account the effect of temperature variation on the viscosity, density, rheological behaviour and oxidation stability. It would be useful to further explore the numerical studies by considering the effect of temperature variation on the viscosity and density of the lubricant.

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