Jurnal Tribologi 41 (2024) 177-191

MYTRIBOS Malaysian Tribology Society

Jurnal Tribologi

Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

Analysis of surface damage characteristics and scuffing prediction in the presence of ZDDP additive and running-in process

Jeng-Haur Horng [1], Thi-Na Ta [1,2*], Yue-Syun Wu [3]

[1] Department of Power Mechanical Engineering, National Formosa University, TAIWAN.
[2] Department of Mechanical Engineering, WuFeng University, TAIWAN.
[3] HIWIN Technologies Corporation, TAIWAN.
*Corresponding author: natt.mta@gmail.com

KEYWORDS

Scuffing
Pitting
Running-in
ZDDP additive
Vibration

ABSTRACT

Scuffing is a surface failure phenomenon observed in sliding-rolling contacts due to high loads and high sliding speeds. The mitigation of scuffing is essential for advancing mechanical system lifetime and increasing operational efficiency. The addition of proper additives or performing suitable operating conditions of running-in process are common methods to prevent scuffing. Therefore, this study investigates the effects of zinc dialkyl dithiophosphates (ZDDP) additive and the running-in process, and their combined impact on the tribological performance, scuffing resistance, surface damage characteristics, and vibration behavior of lubricating oil. Employing the four-ball wear test method under varying applied loads and rotating speeds, the results reveal that the addition of ZDDP additive into the base oil could effectively reduce the occurrence of scuffing and the percentage of pitting ratio at various speeds. Notably, the base oil formulated with 1.5 wt% ZDDP demonstrates superior pitting reduction and anti-scuffing characteristics when compared to the base oil with other ZDDP concentrations. The vibration behavior shows a consistent trend with variations in the friction coefficient for all tests, particularly at the initiation of scuffing. Finally, the application of the true frictional power intensity criterion in predicting the onset of scuffing exhibits notable alignment with experiment results.

Received 1 November 2023; received in revised form 22 January 2024; accepted 14 April 2024.
To cite this article: Horng et al., (2024). Analysis of surface damage characteristics and scuffing prediction in the presence of ZDDP additive and running-in process. Jurnal Tribologi 41, pp.177-191.

1.0 INTRODUCTION

Surface damage of transmission elements is usually caused by excessive wear, pitting, and scuffing. These failures significantly reduce the lifetime of mechanical components. In the factory, these components commonly involve a running-in process after grinding and polishing stages. This process is essential for achieving a smoother contact interface, minimizing lubricant layer failures, and enhancing scuffing resistance (Cavatorta and Cusano, 2000). Some authors (Blau, 2005) have shown that during the running-in process, the surface characteristics, friction and wear gradually reach the steady state performance. Other authors (Cabanettes and Rosén, 2014) reported that the running-in process, examined under controlled operating conditions, removes surface asperities through wear or plastic deformation. This process improves the conformity between mechanical surfaces, reduces the risk of oil film rupture during normal operation, and prevents premature failure. However, the optimal operating conditions of load, speed, and duration for the running-in process to obtain the stable state performance have not been determined.

Zinc dialkyl dithiophosphates (ZDDP) is a widely used anti-wear additive (Farhanal and Syahrullail, 2016). It forms a solid-like reaction tribofilm on rubbing surfaces, effectively preventing metal-to-metal contact (Taylor et al., 2008). The ZDDP additive controls wear mainly by forming a protective phosphate glass-based film on the wear track (Zhang and Spikes, 2016). In the context of the running-in phase, ZDDP additives demonstrate a remarkable impact (Bai et al., 2022). During this critical period, the ZDDP molecules form a tribofilm on the surface, acting as a protective barrier against asperity interactions and minimizing direct metal-to-metal contact. This phenomenon could mitigate wear and friction, thus facilitating a smoother transition from the running-in stage to steady-state conditions. However, due to the environmental hazards associated with the production of sulfur and phosphorus from ZDDP, there has been a growing demand to replace ZDDP with environmentally friendly additives. Despite these environmental considerations, ZDDP exhibits extraordinary anti-wear characteristics and cost-effectiveness compared to other additives such as ionic liquid and nanoparticles (Ta and Horng, 2023). Hence, ZDDP is still a primary anti-wear additive (Omar et al., 2022). In this study, ZDDP is employed to enhance the anti-wear and scuffing resistance of a circulation oil for lubricating various systems in industrial machines, such as gearboxes, bearings, and hydraulic systems., etc. Moreover, the synergy between ZDDP additives and the running-in process may contribute significantly to the longevity and efficiency of lubricated systems. This synergy depends on the interaction between lubricant chemistry, composition of ZDDP additive and metal surfaces, which has not been studied comprehensively.

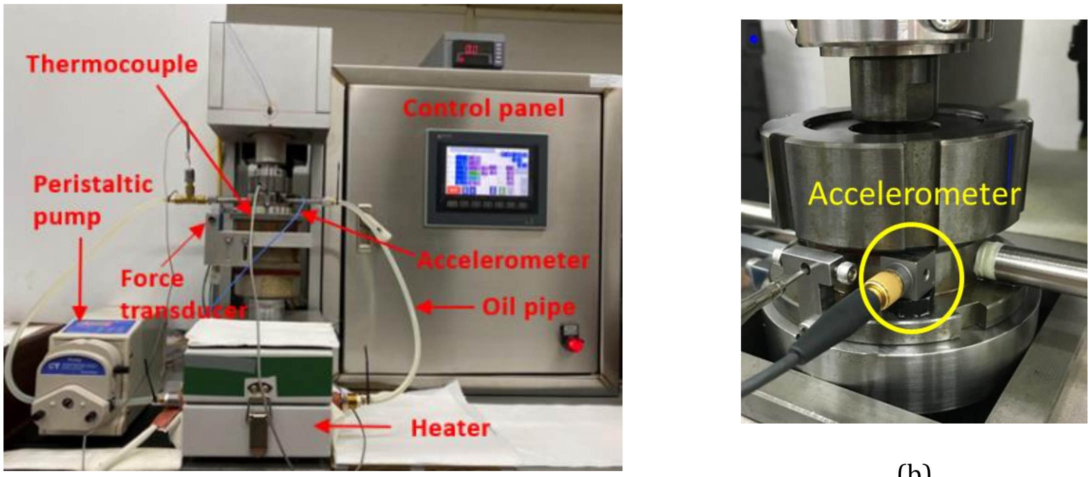
Pitting is a form of surface damage resulting from fatigue wear, and commonly observed in transmission components. As the pits gradually enlarge overtime during the operation of the machine, they contribute to an increasing extent of damage, ultimately leading to component failure. The occurrence of pitting depends on several factors including material properties, lubrication characteristics, surface treatments, thermal influences, and operational parameters such as load, speed, and sliding-rolling ratio (Sun and Bailey, 2018). Some theories and experiments have shown that the beginning of pitting damage can occur during the running-in process at approximately 10^5 cycles (Li, 2015). Hence, the monitoring of the initial and growth of pitting is an important requirement to prevent machine failure. Vibration and noise were considered common detection methods for pitting (Ozturk et al., 2010; Tang et al. 2019). Among these methods, vibration analysis is a relatively mature technique, having successfully applied from the laboratory to industrial applications.

Scuffing is one of the primary failure modes occurring at high-speed, high-load lubricated interfaces. When scuffing occurs, there is severe wear, elevated temperatures, a sudden increase in noise and vibration, and substantial surface plastic deformation. Thus, predicting the occurrence of scuffing phenomenon requires a multidisciplinary approach. Numerous theories and experimental investigations have explored scuffing phenomenon. For instance, in the theoretical aspect, the adiabatic shear instability criterion proposed by Ajayi et al., 2013 and Zhang et al., 2020 has shown that scuffing arises from the competition between frictional heating and work hardening within subsurface materials. Different criteria have been derived from empirical findings to predict the occurrence of scuffing, including the critical contact temperature, thermoelastic instability, friction power intensity (FPI), and lubricant film rupture. Notably, one of the earliest benchmarks is the critical maximum contact temperature, as initially proposed by (Blok, 1937), which continues to be employed in industrial applications. This criterion showed that within any given lubrication system, comprised of distinct lubricants and materials, the onset of scuffing occurs once the maximum surface temperature reaches a critical threshold. After an extensive period of verification, it becomes evident that there exists a nonnegligible deviation from this critical value. Hence, Horng et al., 1995, considered the effect of surface roughness on scuffing and suggested the true friction power intensity (TFPI), which is derived from the friction power intensity by dividing the true contact area by the nominal contact area. Some authors (Matsuzaki et al., 2017) found that the accumulation of wear particles can cause severe plastic deformation, resulting in the occurrence of scuffing. Moreover, vibration and noise detection plays an important role in scuffing prediction technology. Experiments by the authors (Ramteke et al., 2020) have shown that the amplitude of vibration and noise increase at the onset of scuffing. Other authors (Ta et al., 2022) found that vibration behavior shows a close correlation with the friction coefficient and the ratio of minimum film thickness to surface roughness (the lambda parameter). Therefore, scuffing is influenced by various factors, but existing literature often examines these factors separately. This study investigates the combined impacts of ZDDP additive and the running-in process on surface damage characteristics, including wear, pitting and scuffing. These combined impacts have not been studied sufficiently. For instance, the authors (Ueda et al., 2022) recently explored the effects of different additives and the running-in process on scuffing. However, they only considered a single additive ratio and did not address pitting. The present study examines the effect of ZDDP at various weight percentages under a designed oil circulation system. Then, the TFPI criterion and vibration data analysis are applied to predict the onset of scuffing.

2.0 MATERIALS AND METHODS

Experimental investigations were conducted using a four-ball wear test machine, as shown in Figure 1. The machine was equipped with an oil circulation system to simulate the hydraulic oil flow of factory machinery, which has not been considered in previous studies. The base oil used for testing was a paraffinic base oil (R100), which has a density of 0.886 g/cm^3, and a viscosity of 100.2 cSt at 40^{o}C. One of the main objectives of the study is to improve the scuffing resistance of lubricants for lubricating transmission elements. To achieve this, the circulation oil R100 was chosen as the base oil, and the test material was selected from commonly used materials in manufacturing transmission components. Thus, AISI 52100 steel balls with a diameter of 12.7 mm, and a hardness of 62-66 HRC, were used as the testing material. To examine the influence of the ZDDP, different weight percentages, as indicated in Table 1, were added to the base oil.

The test procedure was carried out in two stages. In the first stage, referred to as the running-in process, the experiments were performed at an applied load of 40 kgf, a rotating speed of 600 rpm, and a rubbing time of 60 minutes, according to the standard test ASTM D2266-01 (2015). Subsequently, in the second stage, the applied load was varied from 20 to 110 kgf at intervals of 30 kgf every 2 minutes. Additionally, three sets of rotational speeds for the upper ball (600, 900, and 1200 rpm) were employed. The experimental conditions were chosen based on the range of contact pressures experienced by transmission components in the industry, where mean pressures typically range from 1.0 to 2.0 GPa for gear contacts and 1.0 to 3.5 GPa for rolling bearings (Zhang and Spikes, 2020). In cases where the running-in process was not considered, the first stage of the experiment was excluded. To measure vibration, an accelerometer was affixed to the lower specimen as shown in Figure 1(b). Each test condition was repeated at least three times, and the error bars on wear results represent the standard deviation observed across these three test repetitions. After each test, the surface morphology and diameter of wear scars on steel balls were analyzed using optical microscopy (OLYMPUS STM6).



(a) (b)

Figure 1: (a) Four-ball tester, and (b) position of the accelerometer.

Table 1: The test sample and lubricant contents.

Test	Symbols	Lubricant contents
No. 1	R100	R100
No. 2	0.25 ZDDP	R100 + 0.25 *wt*% ZDDP
No. 3	0.5 ZDDP	R100 + 0.5 *wt*% ZDDP
No. 4	1.0 ZDDP	R100 + 1.0 *wt*% ZDDP
No. 5	1.5 ZDDP	R100 + 1.5 *wt*% ZDDP

3.0 RESULTS AND DISCUSSION

Figure 2 shows a comparison of the friction coefficients of the base oil (R100) under the speed of 900 rpm with and without the running-in process. Scuffing was observed during the abrupt peaks of the friction coefficient throughout the testing process. The presence of the running-in process resulted in delayed scuffing. This could be attributed to the formation of a better bearing surface at the end of the running-in process, leading to increased real contact area, improved lubrication conditions, and delayed onset of scuffing. However, once the running-in process is complete, the initial tribofilm that was formed during the running-in may start to break down or undergo changes, resulting in a higher coefficient of friction (COF) at the second phase of the test.

The rotational speed plays an important role in influencing scuffing. The changes in the COF of the base oil R100 compared to that of the test added 1.5 wt% ZDDP are shown in Figure 3. The presence of scuffing in the tests of R100 was observed at the speeds of 900 and 1200 rpm. This could be attributed to the fact that at higher rotating speeds, the contact between mating surfaces intensifies, leading to elevated frictional forces and thermal energy generation. This heightened energy can accelerate the onset of scuffing by promoting adhesive interactions between the contacting surfaces. The incorporation of ZDDP additives has demonstrated effectiveness in preventing scuffing, as indicated by the absence of scuffing observations at all tested speeds (shown by the dashed lines in Figure 3).

The changes in the temperature of tested lubricants during the wear test at different speeds are shown in Figure 4. The temperature increased with the applied load and speed. Notably, when scuffing occurred, the temperature spikes were observed, consistent with the tendency of friction coefficient in Figure 3 for the test using base oil R100 at the speed of 1200 rpm. The addition of ZDDP led to higher lubricant temperatures compared to the base oil under the same operating conditions. This could be attributed to the formation of rough and patchy phosphate-based films at the contact interface, resulting in a higher COF and causing temperature rise (Dawczyk et al., 2019). However, the absence of ZDDP caused more fluctuations in oil temperature at higher loads and speeds, affecting the viscosity of the oil and allowing scuffing.

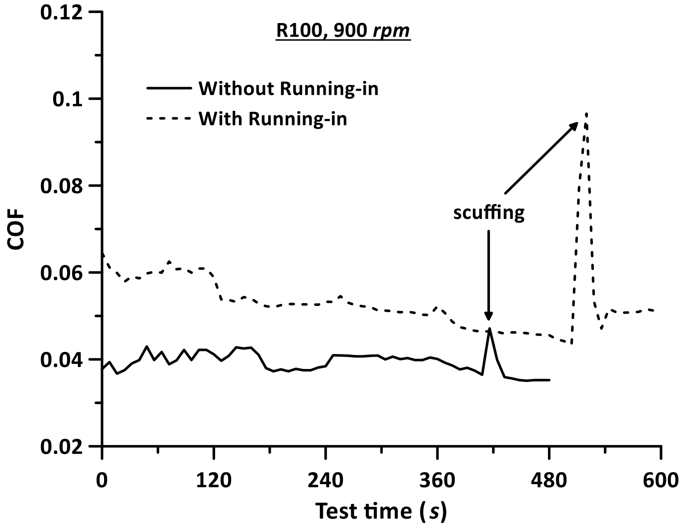


Figure 2: Friction coefficient of the base oil with and without running-in process.

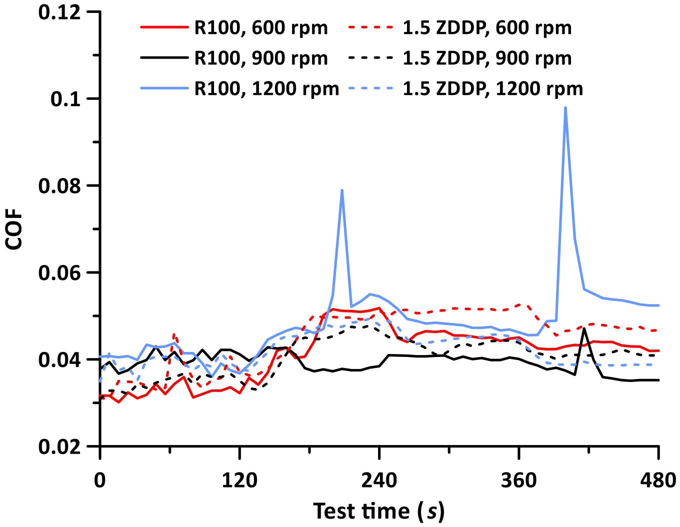


Figure 3: Friction coefficient at different rotating speeds without the running-in process.

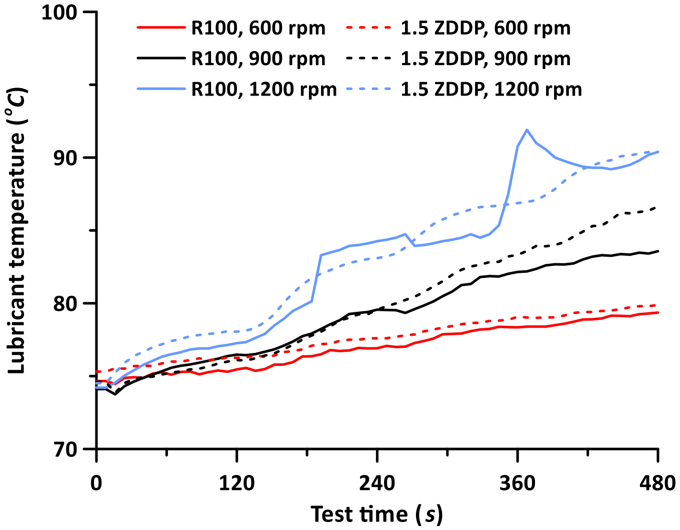


Figure 4: Variation in lubricant temperature at different speeds without the running-in stage.

The variation in COF of the tests added different concentrations of ZDDP additive during the step loading stage after the running-in process is shown in Figure 5. The COF exhibits a progressive decline as the applied step load increases, eventually leading to scuffing failure. Scuffing remained absent before reaching the step-loading stage of 110 kgf. The addition of ZDDP into the base oil resulted in a delayed onset of scuffing compared to that of the test with R100. With ZDDP concentrations up to 1.5 wt%, there exists a direct correlation: higher ZDDP concentrations correspond to later instances of scuffing occurrence. However, the COF for different concentrations of ZDDP was higher compared to that of the base oil. This observation suggests that the addition of ZDDP additive leads to the formation of a solid-like reaction film at the contact interfaces after the running-in process (Taylor et al., 2008). This tribofilm inhibits the entrainment of fluid film to the contact region, resulting in a higher contact load ratio between contact surfaces and increased friction. Additionally, the lubricant with 1.5 wt% ZDDP added consistently exhibited a lower friction coefficient compared to other tests including ZDDP additives (tests No. 2, 3, 4) with the running-in process. To confirm the formation of ZDDP tribofilm, scanning electron microscopy/energy-dispersive X-ray spectroscopy (SEM/EDX) analysis was performed on the wear tracks after the wear process. In addition to the elements present in the chemical composition of AISI 52100 steel material (such as Fe, Cr, C, Si), the formation of ZDDP tribofilm was indicated by the distribution of phosphorus, zinc, and sulfur elements on the wear scar region, as shown in Figure 6. Elemental phosphorus (P) found on the wear track could be attributed to the formation of phosphate tribofilm due to the tribochemical reaction between the additive with rubbing surfaces at high temperature. This observation aligns with previous research findings (Hsu et al., 2017; Dawczyk et al., 2019), regarding the characteristics of phosphate films.

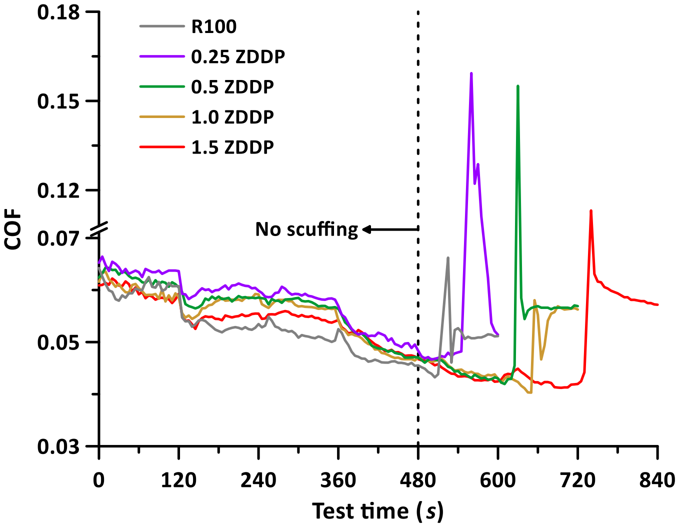


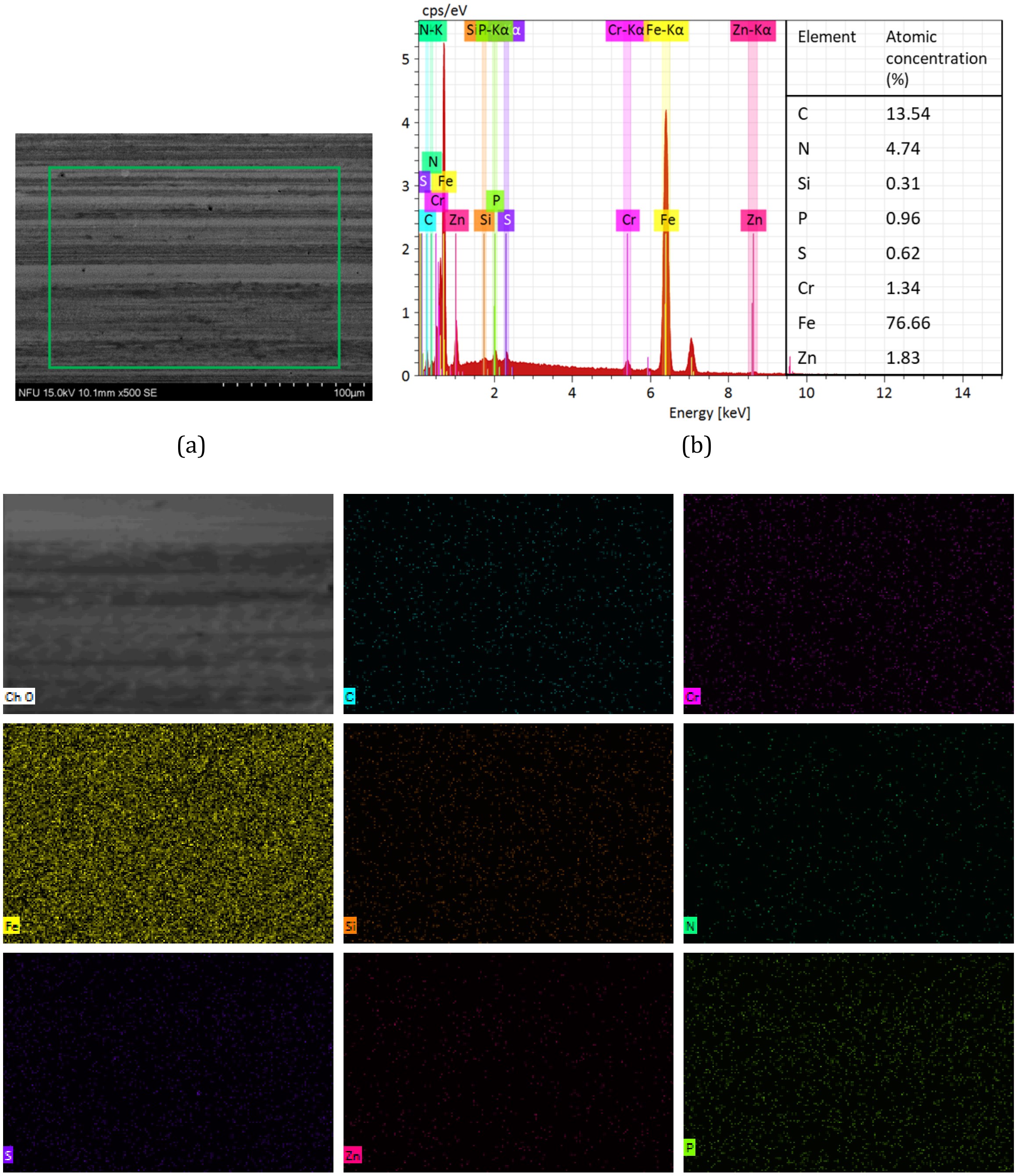
Figure 5: The COF of all tested lubricants at 900 rpm with running-in process.

The diameters of the wear marks produced on the steel ball after the wear process were measured to evaluate the anti-wear characteristic of ZDDP additive. The average wear scar diameter (WSD) of the three stationary balls at different concentrations of ZDDP and various speeds are shown in Figure 7. The error bars in this figure represent the standard deviation between three experiments under the same test conditions. The results showed that the WSD for the tested oil R100 at 600 rpm was approximately 498 µm, then increased by 2.7, and 3.6 times at 900 rpm and 1200 rpm, respectively. It is worth noting that the occurrence of scuffing, as shown by the tests with the base oil at speeds of 900 and 1200 rpm in Figure 3, corresponded to considerable WSD values. When different weight percentages of ZDDP were added to the R100, the WSD showed slight changes with speed. Compared with the tendency of the COF in Figure 5, the addition of ZDDP led to an increase in friction and a reduction in wear. This observation on tribological performance of ZDDP is in good agreement with previous studies (Yang et al., 2021).

The analysis results of the percentage of pitting area on the wear scars are indicated by red dots in Figures 8-9. Figure 8 provides a comparative analysis of the pitting area percentages observed in the test of R100 under the incremental loads at various speeds without the running-in stage. Notably, at the rotational speed of 600 rpm, the calculated pitting area ratio was 8.9%. This value increased to 17.5% when the rotational speed was increased to 900 rpm, and further to 17.8% when reaching 1200 rpm. These findings illustrate a direct correlation between the pitting area ratio and the rotational speed. As the rotational speed was increased, the extent of both pitting and wear surfaces became more pronounced, indicating a progressive deterioration in the contact surfaces. This can be explained by the fact that higher rotational speeds lead to more rapid and intense interactions between the contacting surfaces. These interactions generate elevated stresses and heat, which can contribute to the initiation and propagation of pitting damage. The increased pitting area percentage indicates a greater extent of surface damage and the importance of managing operating conditions, especially at high-speed rotations.

The variation in the percentage of the pitting ratio of the test added different concentrations of ZDDP additive including the running-in stage is shown in Figure 9. As ZDDP was introduced into the tested oil, its presence prompted the formation of protective tribofilms on contacting surfaces, resulting in friction and wear reductions. The percentages of pitted areas for the tests with 0.5 wt% ZDDP (No. 3) and 1.5 wt% ZDDP (No. 5) were approximately 5%, and the other tests exceeded 20%. The application of a proper ZDDP concentration depends on the specific operational conditions, the material of friction pairs, and lubricants. Higher concentrations of ZDDP may enhance protection against stress concentrations and surface fatigue, thereby potentially reducing the occurrence and extent of pitting damage. However, excessively high concentrations might lead to detrimental effects such as additive depletion and the potential for chemical interactions resulting in unintended surface reactions. Some studies (Vrcek et al., 2019) found that the formation of ZDDP tribofilm increases the growth of micropitting in rolling-sliding contacts, achieved through the reduction of wear (Figure 7) and increase in the friction coefficient (Figure 5). Therefore, the appropriate utilization of ZDDP can effectively reduce pitting occurrences. In this study, the addition of 1.5 wt% ZDDP exhibited better pitting reduction compared to the other tested concentrations.

The root mean square (RMS) values of total acceleration vibration during the test conducted at 900 rpm with the running process are shown in Figure 10. The trends observed in the magnitudes of acceleration for all tested lubricants were similar to those of the friction coefficients in Figure 5. The total vibration increased dramatically at the onset of scuffing. Interestingly, for the circulation oil containing ZDDP, total vibrations were higher than that of the base oil. However, this contrasted with wear behavior in Figure 6. It could be speculated that the presence of irregular and uneven phosphate-based films from ZDDP potentially prevented surface damage and minimized wear effects but simultaneously led to higher pre-scuffing friction and vibration levels.



Element	Atomic concentration (%)
C	13.54
N	4.74
Si	0.31
P	0.96
S	0.62
Cr	1.34
Fe	76.66
Zn	1.83

(a) (b)

(c)

Figure 6: (a) The SEM image, (b) EDS analysis result, and (c) element distribution on the wear surface lubricated with 1.5 wt% ZDDP additive.

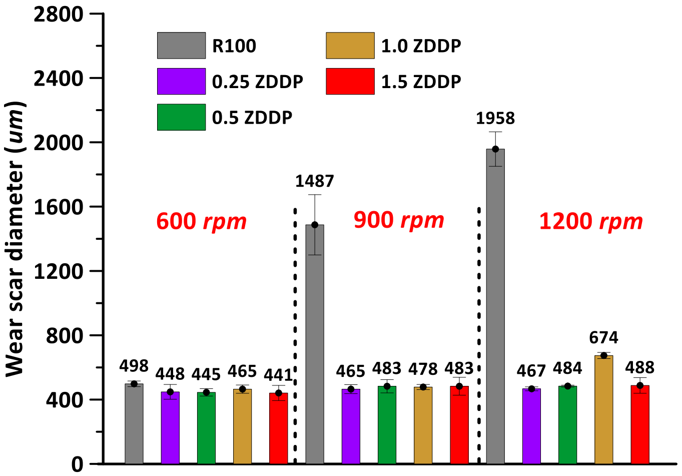
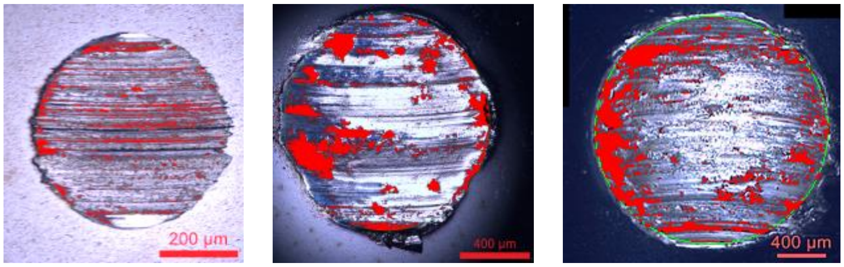
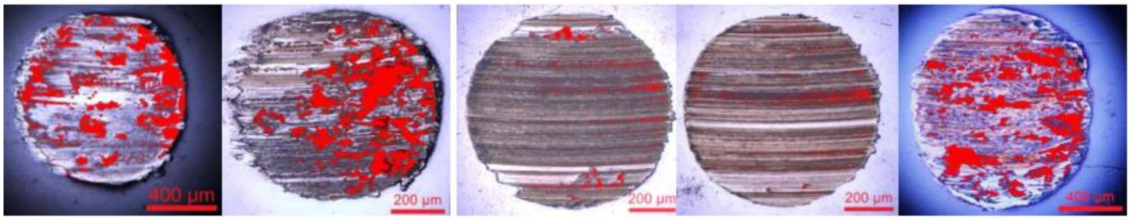


Figure 7: Averaged WSD at different contents of ZDDP and speeds without running-in process.



(a) 8.9% (b) 17.5% (c) 17.8 %

Figure 8: Pitting analysis results on the steel balls of the base oil without the running-in process at the speeds of (a) 600, (b) 900, and (c) 1200 rpm.



No. 1: 22.5% No. 2: 25.9% No. 3: 5.3% No. 4: 20.5% No. 5: 4.7%

Figure 9: Pitting analysis results of the tests at 900 rpm with the running-in process and different concentrations of ZDDP.

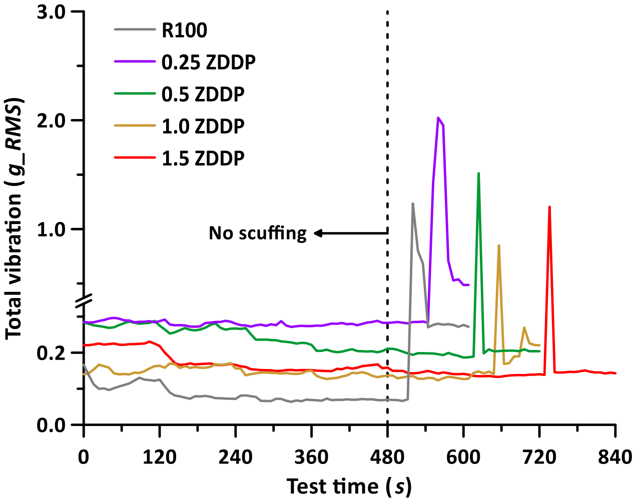


Figure 10: Total vibration variations at different contents of ZDDP during the step loadings.

Some studies have shown that surface roughness plays an important role in influencing the occurrence of scuffing (Wojciechowski et al., 2016). Therefore, this study employed a modified version of the FPI criterion, called true friction power intensity (TFPI). In the FPI, the rate of friction heat per unit nominal contact area is given by μPV_s, where μ, P, V_s are the COF just before scuffing, nominal pressure, and sliding velocity, respectively. The TFPI is derived from the FPI by dividing the true contact area by the nominal contact area (A_t/A_n). The A_t/A_n is calculated using the equations proposed by Li et al., 2010 as follows:

$$\frac{A_t}{A_n} = (0.47 + 0.53\,exp(-0.87\psi^{1.12}))(F^*)^{1-exp(-2.7\psi^{0.35})} \tag{1}$$

where $F^* = F/(A_nY)$ is dimensionless normal load, and Ψ is the plasticity index which is calculated as:

$$\psi = \frac{2E}{C_v\pi(1-v^2)Y}\left(\frac{\sigma_s}{\rho}\right)^{0.5} \tag{2}$$

where σ_s is the standard deviation of asperity heights, and the ratio of σ_s to the standard deviation of surface heights (σ) is defined as:

$$\frac{\sigma_s}{\sigma} = \sqrt{1 - \frac{3.717 \times 10^{-4}}{\beta^2}} \tag{3}$$

where $\beta = \eta\rho\sigma$ is the roughness parameter, with η and ρ denote the asperity density, and the asperity tip radius of curvature, respectively.

The evolution of roughness height (σ) during the step-loading process at the speed of 900 rpm is shown in Figure 11. It can be observed that the higher the concentration of ZDDP results in smoother surfaces. The reduction in surface roughness due to higher ZDDP concentrations suggests that the additive could prevent the micro-scale asperities on the surface from coming into direct contact, consequently reducing pitting and preventing scuffing. Furthermore, roughness patterns and the height of asperities on a contact surface are related to areas that serve as oil reservoirs, affecting the occurrence of scuffing. Thus, in the evaluation of scuffing within the context of the true friction power intensity (TFPI) criterion, these surface roughness characteristics play a critical role. It is noteworthy that a high roughness height consistently aligns with a high TFPI value just before scuffing for certain roughness patterns (Horng et al., 1995).

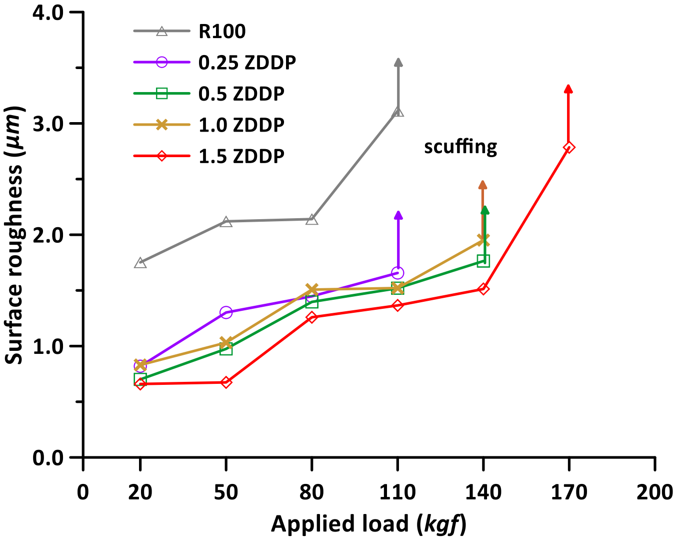


Figure 11: The change in surface roughness during the step loadings process of the test with different concentrations of ZDDP additive.

The variation of the TFPI during the step loading process for the tested oil formulated with different concentrations of ZDDP additive after the running-in process is shown in Figure 12. The TFPI value of the base oil R100 demonstrates the highest value, which may easily approach scuffing. In most cases, the higher the concentration of ZDDP the lower the TFPI value at the same step loading stage. The base oil formulated with 1.5 wt% ZDDP exhibited the highest resistance to scuffing among all tested lubricants, as evidenced by its higher TFPI value before scuffing at 170 kgf. This result shows good agreement with the observed trend in the COF as presented in Figure 5.

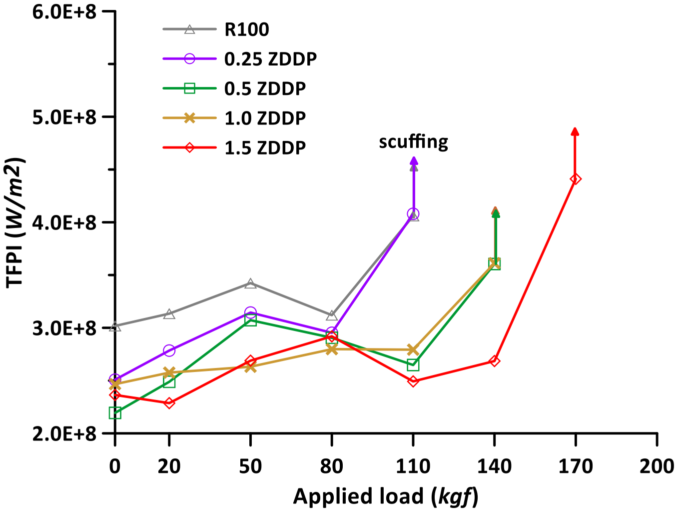


Figure 12: The change of TFPI at different contents of ZDDP during the step loadings.

CONCLUSIONS

This study aimed to investigate the effects of the addition of ZDDP additives and the running-in process on the surface damage characteristics, and tribological and vibration behaviors. The percentage of pitting ratio on wear scar area and the onset of scuffing were analyzed. The main obtained results are summarized as follows:

1. The presence of the running-in process, regardless of the addition of ZDDP additive, contributed to a delayed onset of scuffing.
2. With the addition of different ZDDP concentrations to the base oil, the presence of the running-in process resulted in higher friction coefficients compared to the tests without the running-in process. This could be attributed to the formation of tribofilm from ZDDP after the running-in process. However, the introduction of ZDDP led to a reduction in wear and pitting. Especially, the addition of 1.5 wt% ZDDP exhibited better anti-wear characteristics and surface damage reduction than the other tested concentrations. These findings provide insights for the development of more effective lubricants used in transmission elements.
3. The RMS value of vibration exhibited a similar trend to the friction coefficients during the step-loading process, particularly at the scuffing initiation and after scuffing.
4. The TFPI criterion presented high reliability in predicting the onset of scuffing when the TFPI values showed a good alignment with experiment results.

ACKNOWLEDGMENTS

This work has initially been accepted and presented at the ICE-SEAM 2023. The authors gratefully acknowledge the financial support of National Science and Technology Council, Taiwan (ROC) under the contract NSTC 111-2622-E-150-001.

REFERENCES

Ajayi, O. O., Lorenzo-Martin, C., Erck, R. A., & Fenske, G. R. (2013). Analytical predictive modeling of scuffing initiation in metallic materials in sliding contact. Wear, 301, 57-61.

ASTM D2266-01 (2015). Standard test method for wear preventive characteristics of lubricating grease (four-ball method).

Bai, L., Meng, Y., Zhang, V., & Khan, Z. A. (2021). Effect of surface topography on ZDDP tribofilm formation during running-in stage subject to boundary lubrication. Tribology Letters, 70, 10.

Blau, P. J. (2005). On the nature of running-in. Tribology International, 38(11-12), 1007-1012.

Blok, H. (1937). Surface temperature measurements on gear teeth under extreme pressure lubricating condition. Proceeding of the Institution of Mechanical Engineers, 2, 14-20.

Cabanettes, F., & Rosén, B. G. (2014). Topography changes observation during running-in of rolling contacts. Wear, 315(1-2), 78-86.

Cavatorta M. P., & Cusano C. (2000) Running-in of aluminum/steel contacts under starved lubrication: Part II. Effect on scuffing. Wear, 242(1-2), 133-139.

Dawczyk, J.,·Morgan, N,·Russo, J., & Spikes, H. (2019). Film thickness and friction of ZDDP tribofilms. Triboly Letter, 67, 34.
doi:10.1177/13506501231198571.

Farhanah, A. N., & Syahrullail. Evaluation of lubrication performance of RBD palm stearin and its formulation under different applied loads. Jurnal Tribologi, 10, 1-15.

Horng, J. H., Lin, J. F., & Li, K. Y. (1995). Effect of surface roughness on steel roller scuffing. Wear, 184(2), 203-212.

Horng, J. H., Lin, J. F., & Li, K. Y. (1996). Scuffing as evaluated from the viewpoint of surface roughness and friction energy. Journal of Tribology, 118(3), 669-675.

Hsu, C. J., Stratmann, A., Rosenkranz, A., & Gachot, C. (2017). Enhanced growth of ZDDP-based tribofilms on laser-interference patterned cylinder roller bearings. Lubricants, 5(4), 39.

Li, L., Etsion, I., & Talke, F. E. (2010). Contact area and static friction of rough surfaces with high plasticity index. Journal of Tribology, 132, 031401.

Li, S. (2015). A computational study on the influence of surface roughness lay directionality on micropitting of lubricated point contacts. Journal of Tribology, 137, 021401.

Matsuzaki, Y., Yagi, K., & Sugimura, J. (2017). In-situ fast and long observation system for friction surfaces during scuffing of steel. Wear, 386-387, 165-172.

Omar, A. A. S., Salehi, F. M., Farooq, U., Neville, A., & Morina, A. (2022). Effect of zinc dialkyl dithiophosphate replenishment on tribological performance of heavy-duty diesel engine oil. Tribology Letters, 70, 24.

Ozturk, H., Yesilyurt, I., & Sabuncu, M. (2010). Detection and advancement monitoring of distributed pitting failure in gears. Journal of Nondestructive Evaluation, 29, 63-73.

Ramteke, S. M., Chelladurai, H., & Amarnath, M. (2020). Diagnosis of liner scuffing fault of a diesel engine via vibration and acoustic emission analysis, Journal of Vibration Engineering and Technologies, 8, 815-833.

Sun, Y.; & Bailey R. (2018). Effect of sliding conditions on micropitting behaviour of AISI 304 stainless steel in chloride containing solution. Corrosion Science, 139, 197–205.

Ta, T. N., & Horng, J. H. (2023). Evaluation of tribological behavior of a circulation oil with ionic liquid and hybrid additives. Part J: Journal of Engineering Tribology.

Ta, T. N., Horng, J. H., & Hwang, Y. L. (2022). Correlation between tribological and vibration behaviors in sliding lubricated contacts. Journal of Tribology, 144(11), 111603.

Tang, J., Li, J., Wang, H., Wang, Y., & Chen, G. (2019). In-situ monitoring and analysis of the pitting corrosion of carbon steel by acoustic emission. Applied Sciences, 9, 706.

Taylor, L., Dratva, A., & Spikes, H. A. (2008). Friction and wear behavior of zinc dialkyldithiophosphate additive. Tribology Transactions, 43(3), 469-479.

Ueda, M.; Spikes, H.; & Kadiric, A. (2022). In-situ observation of the effect of the tribofilm in rolling-sliding contact. Tribology Letters, 70, 76.

Vrcek, A., Hultqvist, T., Baubet, Y., Marklund, P., & Larsson, R. (2019). Micro-pitting damage of bearing steel surfaces under mixed lubrication conditions: effect of roughness, hardness and ZDDP additive. Tribology International, 138, 239-249.

Wojciechowski, L., Kubiak, K. J., & Mathia, T. G. (2016). Roughness and wettability of surfaces in boundary lubricated scuffing wear. Tribology International, 93, 593-601.

Yang, S., Zhang, D., Wong, J. S. S., & Cai, M. (2021). Interactions between ZDDP and an oil-soluble ionic liquid additive. Tribology International, 158, 106938.

Zhang, C., Peng, B., Gu, L., Wang, T., & Wang, L. (2020). A scuffing criterion of steels based on the friction-induced adiabatic shear instability. Tribology International, 148, 106340.

Zhang, J., & Spikes H. (2016). On the mechanism of zddp antiwear film formation. Tribology Letters, 63, 24.

Zhang, J., & Spikes H. (2020). Measurement of EDH friction at very high contact pressures. Tribology Letters, 68, 42.