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Effect of lubricant contamination on friction and wear in an EHL sliding contact

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Nomenclature

a - contact half width, m; C - contaminant concentration, g/l; E - Young's modulus, GPa; E' - dimensionless elasticity modulus, Pa; f - frequency, Hz; P_h - maximal hertzian pressure, MPa; Ra - roughness, μm; R_x - radius of relative curvature, m; S - stroke length, μm; W - normal load, N; $U1$ - ball velocity, m/s; $U2$ - disk velocity, m/s; ν_0 - kinematic viscosity at the reference temperature and pressure (T_0, P_0), Cst; ν - Poisson ratio.

1. Introduction

Lubricants, which play an important role in wear and friction reduction, inevitably contain solid contamination particles. These undesirable particles can be generated within machine components by abrasion and adhesion, or perhaps entrained into the lubricating oil from the surroundding environment. Such particles become one of the major causes of failure of a tribological system. They damage surfaces and lead to fatigue and wear of machine elements.

In recent years, several authors have experimentally and numerically studied the effect of lubricant contamination on an elastohydrodynamic lubrication (EHL) contact. The entry and deformation of particles in an EHL contact have been studied experimentally [1-5]. In these studies, the optical interferometry technique is used to follow the particle behavior in the contact. By theoretical means, many authors have calculated the pressure field in the presence of a dent on the surfaces [6-11]. They showed that a dent increases the stress in the solid surfaces. Other authors have focused their attention on the evolution of the dent in the contact and its effect on the oil film thickness [12-14].

Recently, models which take into account the effects of solid particles in an EHL contact have been developed by Nikas [15], and by Kang et al. [16]. In a previous work authors [17] have presented an original experimental study, showing the effect of solid particles on gear wear. They demonstrated that the presence of sand particles in oil suspension leads to significant wear in the first few operating cycles in the zones with a high rate of sliding.

Kreivaitis et al. [18] undertook a study by using a four ball tribometer in order to investigate tribological behavior of rapeseed oil mixtures with mono and diglycerides. This study gives detailed pictures on the possible reason of wear and friction reduction by the investigated mixtures. Shyshkanova [19] perform a study which consists to evaluate the effect of friction on contact problems. In this research, three dimensional contact problem is investigated taking into account friction, adhesion and roughness.

Other techniques have been used for the prediction the effect of solid contaminants on surface contact. Among these techniques, vibration analysis and used oil analysis constitute excellent diagnostic tools in maintenance. Vahajoa [20] undertook a study using various oil analysis methods in order to determine the wear of metals in working fluids. Motylewski et al. [21] also undertook an experimental study for determining the contamination level and wear severity by using photo-acoustic investigation. Peng et al. [22] demonstrates the important role of vibration and oil analysis in machine condition monitoring and fault diagnosis. In his study, fault detection obtained by vibration signature is compared with the particle analysis.

In the present paper, the high frequency reciprocating rig (HFRR) machine has been used to investigate the effect of solid contamination of lubrication on wear and friction performances of machine components in a pure sliding EHL contact.

2. Experimental detail

2.1. Experimental device

The friction and wear performance of surface contact were evaluated using the HFRR Fig. 1 shows a schematic diagram of the HFRR device. This device measures the friction and wear under boundary lubrication conditions. The principle elements are a reciprocating 6.00 mm diameter harder ball on a softer steel disk. Both the ball and the disk are made of AISI 52100 steel. Tests were carried out under the fully submerged oil condition at different normal load and different contaminated solution. The oil temperature was controlled by a heater block longitudinally restrained by a piezoelectric force transducer which measures the friction force generated between the ball and disk. In sliding contact the formation of oil film was measured by the electrical contact potential (ECP) technique.

A wear track produced on the steel ball surface was observed using optical microscopy.

2.2. Material

2.2.1. The lubricant

The lubricant used is PAO 8. It is a synthetic base lubricating oil having a kinematic viscosity $\nu_0 = 46.8$ Cst at T_0 = 40°C. This oil can be used in many industrial and automotive lubricant applications like gearboxes, compressors and hydraulic installations.

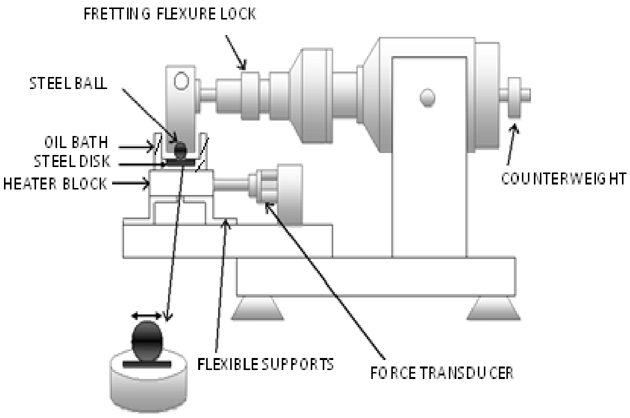


Fig. 1 Schematic diagram of HFRR machine

Table 1

Friction pair disk-ball

Parameters	Ball	Disk
Rx, m	3.00 E-03	∞
E, GPa	210	210
ν	0.3	0.3
Materials	AISI 52100	AISI 52100
Diameter, mm	6.00	15
Thickness, mm	-	3.00
Roughness *Ra*, µm	0.1	0.1

2.2.2. The contaminant

The used contaminant is desert sand which can be conveyed by the wind as far as Europe and even America. It is very rich in silica, with 90% of quartz. It was cleaned and filtered to 40 µm and analyzed chemically. The chemical constitution is given in Fig. 2.

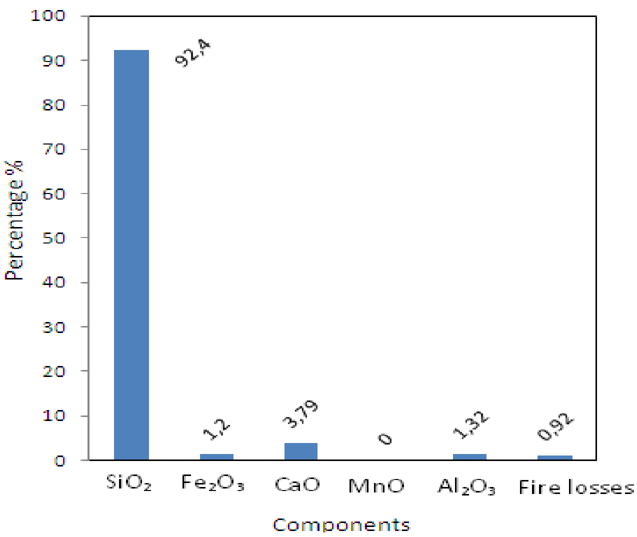


Fig. 2 Chemical constitution of sand

2.2.3. Test parameters

In order to better understand the EHL contact operation, it is important to evaluate the mechanical state and functional parameters. The contact between the ball and disk is circular. Hertzian pressure in this case is given by

$$P_h = \frac{3W}{2\pi a^2} \tag{1}$$

where *a* is the contact half-width

$$a = \left(\frac{3W\,R_x}{2\,E'}\right)^{-1} \tag{2}$$

and *W* is the normal load, R_x is the radius of relative curvature given by

$$R_X = \left(\frac{1}{R_{x1}} + \frac{1}{R_{x2}}\right)^{-1} \tag{3}$$

and E' is the dimensionless elasticity module calculated by

$$E' = \left[\frac{1}{2}\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)\right]^{-1} \tag{4}$$

All test parameters are described in Tables 1 and 2.

Table 2

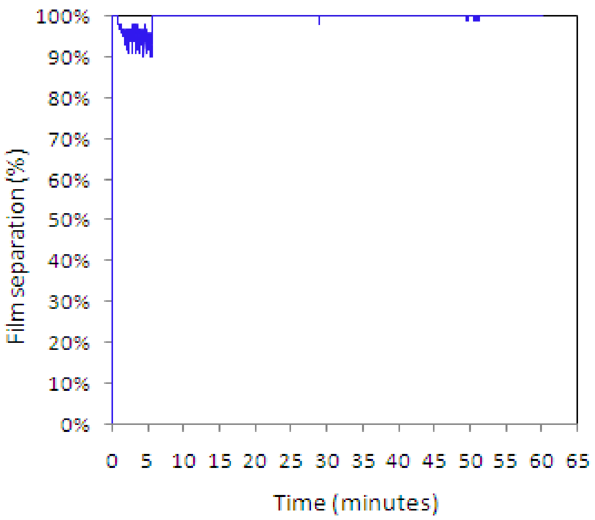
Mechanical state and functional parameters

Parameters	Value	
S, µm	2000	
f, Hz	100	
$n = 60\,f$, rpm	6000	
ω=3.1416 n/30, s^{-1}	628.32	
$U1 = \omega C$, m/s	1.26	
$U2$, m/s	0	
$\lvert U1+U2 \rvert$, m/s	1.26	
$\lvert U1-U2 \rvert$, m/s	1.26	
$\left\lvert \frac{U1-U2}{U1+U2} \right\rvert$, %	100	
W, N	0.981	1.96
a, m	2.67×10^{-5}	3.37×10^{-5}
P_h, MPa	655.284	825.325

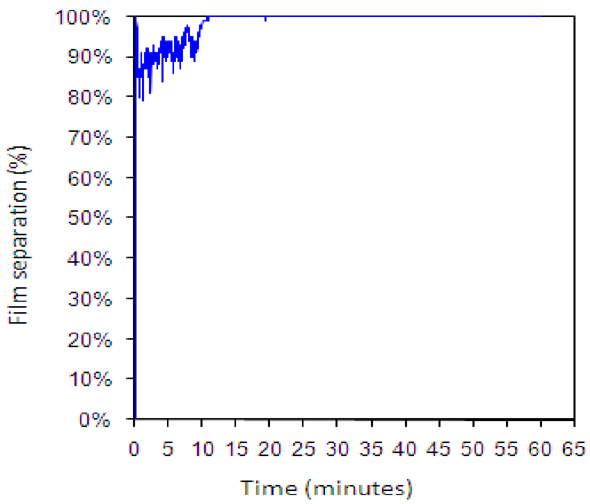
3. Results and discussion

The presence of solid particles in lubricant is inevitable. These undesirable particles cause wear by fatigue or adhesion with surfaces in rolling contact, and by abrasion with surfaces in sliding contact. Generally, the oil film and friction coefficient behavior was measured using a steel ball rubbing against a steel disk under boundary lubrication conditions at different loads and various concentrations of contaminants in the lubricant.

Fig. 3 illustrates the behavior of oil film between the ball and disk at 40°C and normal load of 0.981 N and 1.96 N. The obtained results show more noticeable fluctuations at 1.96 N load than that at 0.981 N in the first few instants of operating time. In this time, the separation is not fully ensured and it has a lower percentage at 1.96 N load than that at 0.981 N. These results can be explained by the increase of contact pressure with load increase and consequently the oil film separation decrease. After this time, the film separation percentage increases and then becomes stable ensuring consequently a full separation (i.e., a minimum oil film thickness).



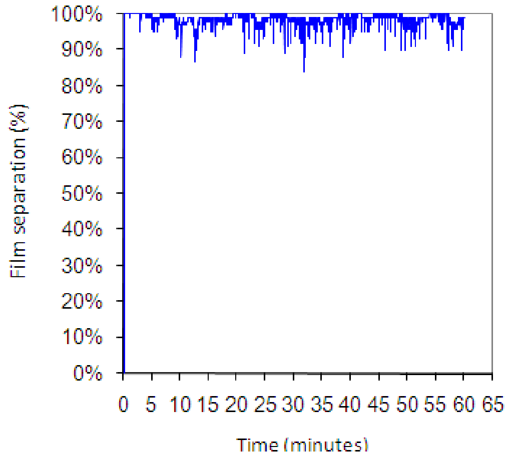
a



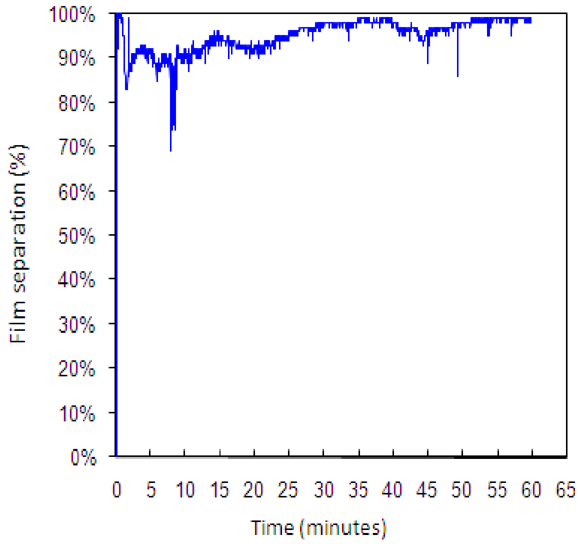
b

Fig. 3 Film formation measuring by ECP technique for lubricant without contaminant presence: a – W = = 0.981 N; b – W = 1.96 N

It is well known that many debris or solid particles will be larger than the oil film thickness in an EHL contacts. Therefore once a particle is entrained into the contact, either it is reduced in size. The effect of the presence of solid particles on oil film separation at 40°C is showed in Fig. 4. Results show clearly that the passage of particles through the contact disturbs the correct operation of mechanisms leading to the significant fluctuations of oil film separation. These fluctuations increase with higher contaminants concentration (Fig. 4, b). This can be explained by the entry of more particles into the contact.



a

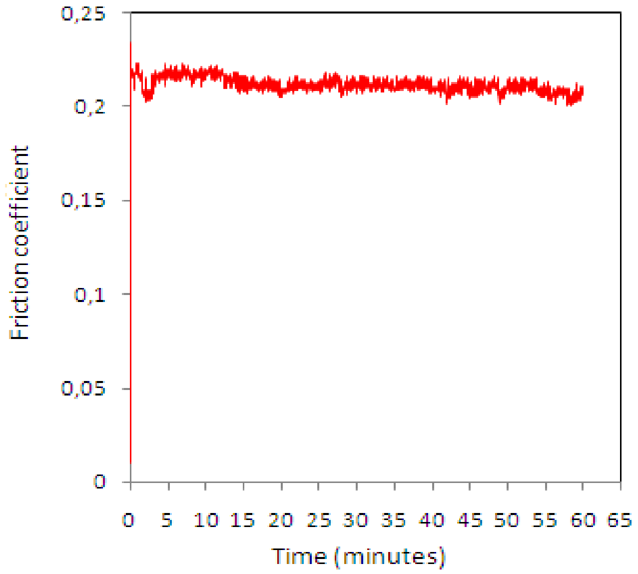


b

Fig. 4 Film formation measuring by ECP technique for lubricant containing various concentrations of contaminant for W = 0.981 N: a - C = 5 g/l ; b - C = = 10 g/l

The evolution of friction coefficient has been studied with run time at normal load of 0.981 N and 1.96 N in an EHL sliding contact for lubricants containing various concentrations of contaminants. The obtained results for friction show a corresponding response to the film formation between surfaces in the boundary lubrication conditions. Fig. 5 shows the variation of friction coefficients for lubricant oil without contaminants, operating at 40°C. The friction appears higher at 1.96 N load than that at 0.981 N. This difference can be explained by the increase of contact pressure leading to decrease of oil film and consequently to friction increase.

In Fig. 6, we observe that friction in the presence of particles which disturb the separation of surfaces exhibits more elevated values compared to operating conditions without the presence of contaminants. Indeed, solid particles have a significant effect on the surface and structure leading to a poor surface quality. Therefore the presence of solid particles in sliding contact leads to significant friction coefficient. In other hand, we observe that the friction coefficient increases with a higher concentration of contaminants in lubricant. This can be explained by the entry of more particles into the contact which accelerates friction.



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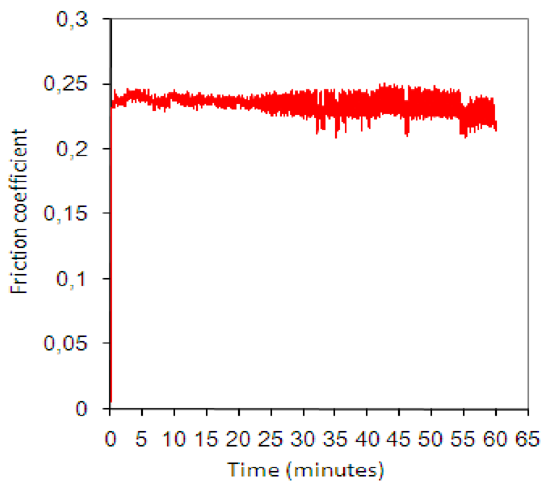
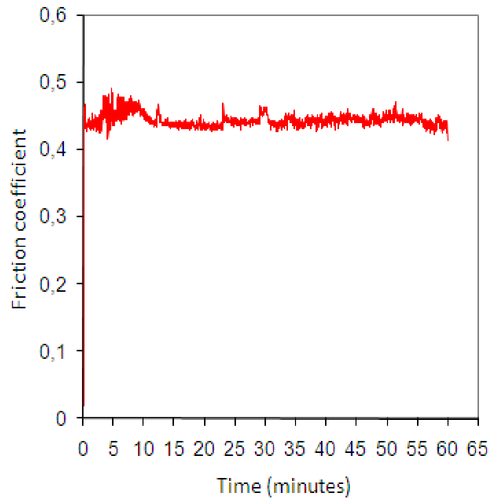


b

Fig. 5 Friction coefficient behaviour for lubricant without the presence of contaminant at T = 40°C: a - W = = 0.981 N; b - W = 1.96 N



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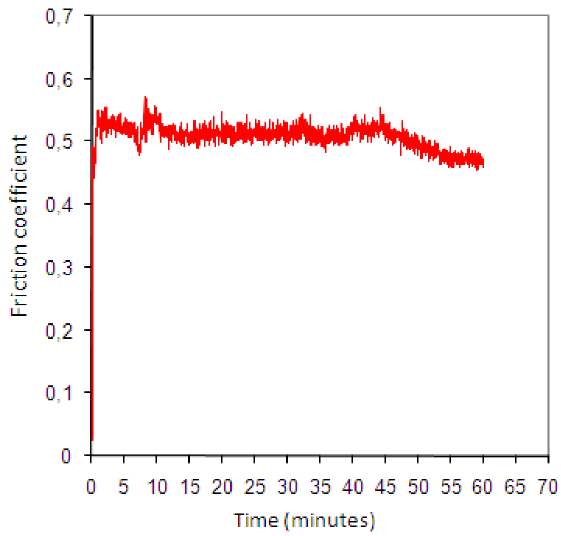

b

Fig. 6 Friction coefficient behaviour for lubricant containing various concentration of contaminant (W = = 0.981 N and T = 40°C): a - C= 5 g/l; b - C = 10 g/l

The effect of temperature variation on friction and oil film separation in a contaminated medium has been studied. The oil temperature was controlled by a heater block. The obtained results (Fig. 7) show that the film separation decreases with temperature increase. This decrease is generally caused by reduction of oil viscosity affected by the oil temperature evolution. In other hand the presence of solid particles in lubricant disturbs proper operation of mechanisms leading to noticeable fluctuations of film separation.

According to Figs. 7 and 8, we note a strong relation between oil film separation and friction coefficient. Indeed, the decreases of oil film separation leads to the increase of friction coefficient (Fig. 8). This increase of friction becomes more elevated with the presence of solid particles. In a purely sliding contact, the presence of these undesirable particles into the contact with an increase of oil temperature accelerates the risk of surfaces damage leading to a poor surfaces quality and consequently to noticeable increase of friction coefficient.

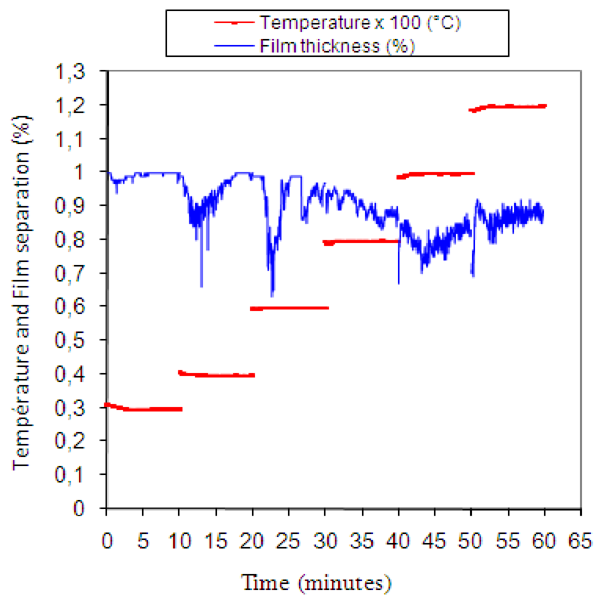

Fig. 7 Influence of contaminant and temperature variation on film separation

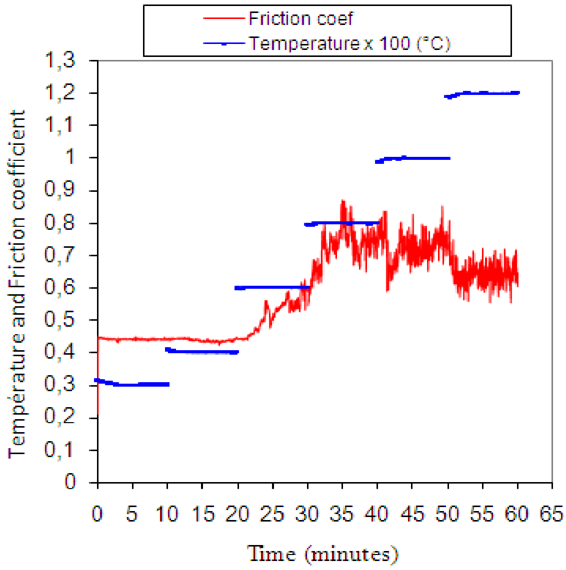

Fig. 8 Influence of contaminant and temperature variation on friction coefficient (W=1.96 N and C = 5 g/l)

For a better understanding of wear phenomenon in a purely sliding contact, photo-micrographic images of steel ball were taken using optical microscopy. Fig. 9 characterizes the ball surface at loads of 0.981 N and 1.96 N

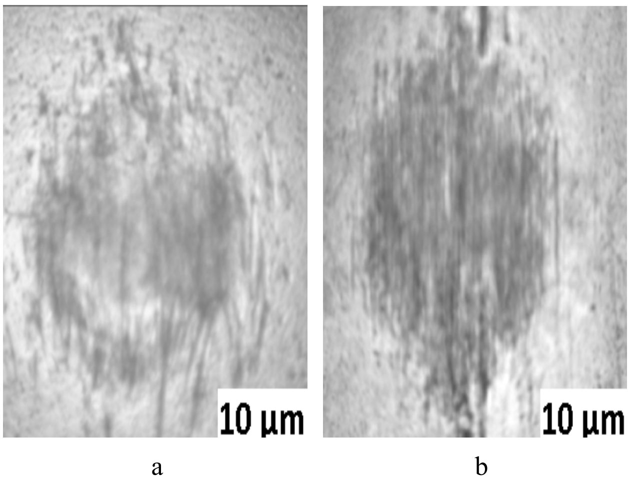

Fig. 9 Optical microscope images ball surface aspect for operating without contaminant presence: a - W = = 0.981 N; b - W = 1.96 N

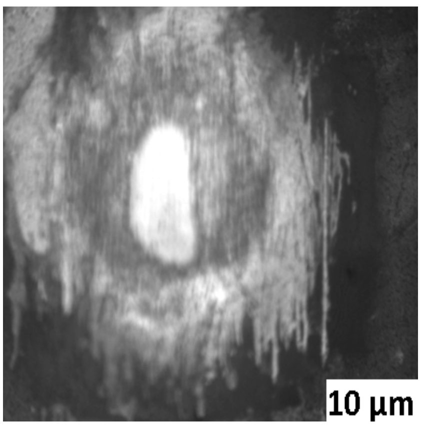

Fig. 10 Optical microscope images ball surface aspect under highly contaminated conditions: C = 5 g/l, W = = 0.981 N

without the presence of contaminants. Figs. 10, 11 and 12 give detailed pictures of the surfaces under highly contaminated conditions. The given results show abrasive wear (furrows, stripes, dents and plastic flow). They are very severe, especially in sliding contact. This wear is accelerated by the presence of sand particles. In Figs. 10 and 11, the presence of dents and furrows is noteworthy for operating with higher concentration of contaminants. The wear becomes more severe (Fig. 12), especially with the presence of particles and operating at higher temperature.

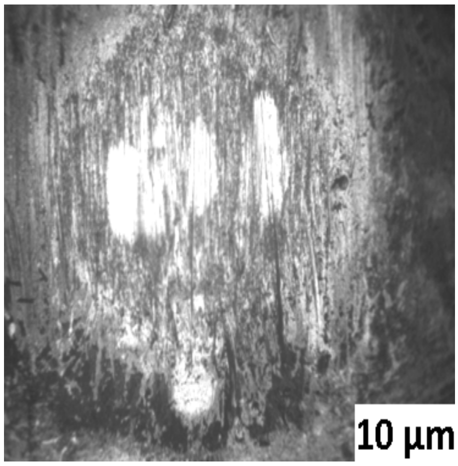

Fig. 11 Optical microscope images ball surface aspect under highly contaminated conditions: W = 0.981 N, C = 10 g/l

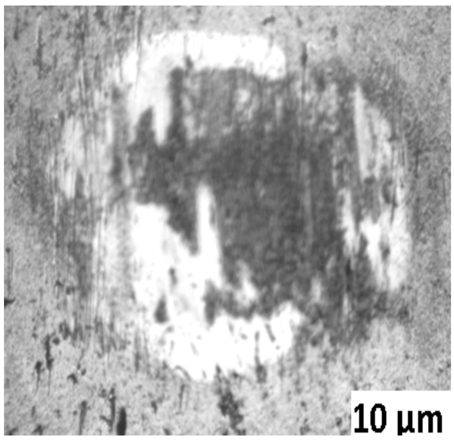

Fig. 12 Optical microscope images ball surface aspect under highly contaminated conditions: C = 5 g/l, W = 1.96 N and temperature variation

4. Conclusion

The principal objectives of this work are twofold. First, we try to evaluate friction coefficient under highly contaminated conditions; and, second, to better understand the effect of solid particles on surfaces wear. With this intention, friction and wear were investigated using the HFRR machine.

From this study, the following conclusions are made:

• The presence of solid particles in the lubricant interferes with the correct operation of lubrication mechanisms.

• The contaminating particles increase the friction coefficient. The friction coefficient is more elevated in the presence of particles compared to operating conditions without the presence of contaminants.

- The friction coefficient is elevated with higher concentration of contaminants in lubricant.
- The results obtained show a strong relation between friction and oil film separation.
- The presence of solid particles with temperature variation leads to oil film reduction and as a consequence the friction increases.
- The presence of solid particles in a purely sliding contact leads to significant wear. In these conditions, the abrasive score marks are indicative.
- The abrasive wear becomes very severe in a contaminated medium with an increase of temperature.

This study confirms that the presence of solid particles in the lubricant has a dual effect: it increases the friction between the surfaces with a relative sliding, and leads to severe abrasive wear. In addition, the presence of particles disturbs the correct operation of lubrication mechanisms and consequently leads to noticeable fluctuations of oil film separation.

Finally, the results obtained help to explain the mechanisms lifespan reduction and constitutes a well contribution in order to understand the role of contamination on friction and machine elements failure.

In future work, we will try to give an explanations of the mechanisms that might relate particles to friction increase by a complete description of the entrainement and deformation of particles into the contact (i.e., how they enter the contact, how they separate films, or starve the contact of oil).

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TEPALO UZTERŠTUMO ITAKA TRINČIAI IR IŠSIDĖVĖJIMUI EHL SLYDIMO KONTAKTE

R e z i u m ė

Šiame straipsnyje aukštojo dažnio grįžtamojo slenkamojo judesio įtaisu nagrinėtas trinties ir mašinų elementų paviršiaus išsidėvėjimas esant visiško tepimo sąlygoms, kintamam apkrovimui ir teršalų koncentracijai. Tyrimai parodė, kad tepale esančios kietos dalelės pažeidžia jo plėvelę, todėl smarkiai keičiasi jos storis, padidėja trinties koeficientas. Tokiomis sąlygomis trintis būna didesnė nei tepant tepalu be teršalų. Be to, kietos dalelės, keičiantis temperatūrai, suplonina tepalo plėvelę ir dėl to trintis padidėja. Siekiant geriau suprasti trinties procesą užterštoje aplinkoje, įtaiso plieninis rutulys buvo stebimas optiniu mikroskopu. Tyrimai parodė, kad abrazyvinę trintį slydimo kontakte padidina smėlio dalelės ir didėjanti temperatūra.

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EFFECT OF LUBRICANT CONTAMINATION ON FRICTION AND WEAR IN AN EHL SLIDING CONTACT

S u m m a r y

In this research friction and surfaces wear of machine elements under fully submerged oil conditions at different load and different contaminant concentration has been studied using a high frequency reciprocating rig (HFRR). The results show that the presence of solid particles in the lubricant disturbs the proper operation of the oil film leading to noticeable fluctuations of film thickness and higher friction coefficient. Under these conditions, friction is elevated compared to its behavior in the absence of contaminants. In addition, the presence of solid particles with temperature variation leads to oil film reduction and as a consequence the friction increases. For a better understanding of wear phenomena in contaminated media, optical microscope images were taken for a steel ball. Results show severe abrasive wear in a purely sliding contact. The wear is accelerated with the presence of sand particles and with a temperature increase.

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ВЛИЯНИЕ ЗАГРЯЗНЕНИЯ В СМАЗКЕ НА ТРЕНИЕ И ИЗНОС В EHL КОНТАКТЕ СКОЛЬЖЕНИЯ

Р е з ю м е

В статье исследовано трение и износ деталей машин в условиях полной смазки, переменного нагружения и концентрации загрязнения прибором высокочастотного возвратно-поступательного движения. Исследования показали, что твердые частицы, находящиеся в смазке повреждают масленую пленку и вызывают значительные изменения её толщины и повышение коэффициента трения. В таких условиях повышается трение по сравнению со смазкой без загрязнения. Кроме того, твердые частицы при изменении температуры вызывают уменьшение смазочной пленки и увеличение трения. Для лучшего понимания процесса трения в загрязненной среде износ стального шара прибора наблюдался оптическим микроскопом. Исследования показали значительное абразивное трение в контакте скольжения. Частицы песка и увеличение температуры повышают трение.

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