Vol. 39, No. 4 (2017) 559-565, DOI: 10.24874/ti.2017.39.04.15

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Characterization of Tribological Properties of Greases for Industrial Circuit Breakers

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Keywords:

Lubricating greases
Wear
Load carrying capacity
Circuit breaker

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A B S T R A C T

Proper grease selection is essential for the electrical industry to minimize friction and wear between the components of circuit breakers under mechanical contact. In this investigation, the tribological properties of commercially available greases for industrial circuit breakers were evaluated. Three tribological tests were performed: the ITeE-PIB Polish Method for testing lubricants under scuffing conditions (extreme pressure, EP), a four-ball test under ASTM D 2266 (anti-wear, AW), and a ball-on-disk test based on ASTM G-99. The worn materials were characterized with an optical 3D profilometer measurement system and a scanning electron microscope (SEM). Additionally, selected greases with the best tribological performance were tested on a testing bench intended for circuit breakers, according to electrical safety standards, which validated the results obtained in the laboratory.

1. INTRODUCTION

One of the main reasons why greases are used as lubricants is due to their ability to stay in the original position where they were applied avoiding re-lubrication, particularly for areas where it is no longer possible. This is due to their high viscosity which allows them to remain in position, whereas other lubricants may not due to the effect of gravity, temperature, load, amongst others [1].

Greases are employed to provide adequate lubrication to reduce friction and prevent harmful wear on components, protect the mechanism against oxidation and corrosion, act as a sealant preventing the passage of contaminating particles, maintain its viscosity regardless of stress or temperature during usage, avoid dripping, not over solidify to avoid undue resistance to motion in cold environments, and tolerate certain levels of contamination, such as humidity, without losing their characteristics significantly [1,2].

Greases are produced from a thickener distributed in a base fluid, that may be either a mineral or synthetic oil, and additives [3]. The friction behavior is highly depending of the grease composition, as explained by De Laurentis et al. [5]. The consistency of the grease depends on the weight percentage of the thickener, generally ranging between 1 to 3 %. These thickeners are employed to retain the base oil in its fibre structure where the most common are calcium, aluminum, sodium, barium, lithium complex, silica, amongst others [2-3]. Finally, the additives may be antioxidants, corrosion inhibitors, extreme pressure (EP) agents, lubricity additives, pour point depressants, and viscosity index improvers. EP agents are activated by reacting with metal surfaces within a specific range of temperature [3].

In the electrical industry, proper grease selection is essential for the correct functioning of the components of electric circuit breakers that are under mechanical contact [6]. According to Salinas [7], switch mechanisms can remain inactive for extended periods with no need for operation; therefore, improper lubrication can result in circuit breaker failure that may potentially cause equipment damage and blackouts. According to Flurscheim [8] low-voltage switches in process plants may have a frequency of operation similar to contractors. However, high-voltage circuit breakers used to control the generators, which activate twice per day to meet the loading requirements, may need to operate several hundred times a year.

Furthermore, an important issue with circuit breakers is that they are not operated with sufficient frequency. Greases and oils for internal lubrication tend to increase their viscosity with the reduction of temperature, and some may solidify with time and lack of movement [9]. Therefore, proper grease selection is required for electric circuit breakers, since there are different types of greases for specific working conditions [8,10]. Cen et al. [11] studied different greases with similar properties used for the same industrial application; he concluded that formulation, thickener material, and base oil properties greatly affect grease performance. Finally, Zheleznyi et al. [12] states that the correct, effective, and rational selection of greases allows a significant reduction of the power consumed to overcome friction in mobile couplings in machines and mechanisms, increasing its useful life and reducing the wear of the contacting surfaces.

In this work, experimental studies of the wear preventive or anti-wear (AW) and EP characteristics of several commercially available lubricating greases were performed in order to provide a methodology for appropriate grease selection for circuit breakers. The tribological properties of wear, load-carrying capacity, and pressure loss limit of greases were determined using a T-02U Four-ball tribotester according to ASTM D 2266 [13] and the ITeE-PIB Polish test method for testing lubricants under scuffing conditions [14]. The coefficient of friction (COF) and wear mass loss were characterized by a T-11 Ball-on-disk test according to ASTM G 99 [15]. Additionally, selected greases that provided the best load-carrying capacity and anti-wear results were tested on circuit breakers at 10,000 cycles in a testing bench order to validate the results in the laboratory.

2. MATERIALS AND EXPERIMENTAL METHODS

The selected commercial greases, base oil, their thickener, viscosity, and temperature range properties obtained from their datasheets are shown in Table 1.

Table 1. Properties of greases selected for the study. NA (not available) denotes that the property was not supplied in the grease datasheet.

Grease	Base oil	Thickener	Viscosity Base oil (cSt)	Temperature Range (°C)
Grease 1	PAO	Clay	30	NA
Grease 2	PAO	Lithium	32.6	-54 to 125
Grease 3	PAO	Lithium	32.6	-54 to 125
Grease 4	PFPE	Silica	510	-25 to 250
Grease 5	Ester	Clay	54	-40 to 150
Grease 6	PAO	Lithium	220	-25 to 140
Grease 7	PAO	Lithium	220	-34 to 177

Table 2. Properties of greases selected for the study. NA (not available) denotes that the property was not supplied in the grease datasheet.

Grease	Drop Point (°C)	Flash Point (°C)	Pour Point (°C)	Penetration (1/10 mm)		
				NLGI grade	Un-worked	Wor-ked
Grease 1	307	NA	NA	1.5	NA	293
Grease 2	NA	250	-62	1.5	297	306
Grease 3	NA	235	-62	2	274	277
Grease 4	NA	None	-20	NA	NA	NA
Grease 5	NA	304	-54	2	248	267
Grease 6	280	NA	-8	2	NA	280
Grease 7	271	NA	NA	2	265	295

Table 2 presents other properties such as drop point, flash point, pour point, and penetration for the same greases. Greases are numbered from 1-7 rather than providing brand names.

2.1. Extreme pressure test (EP)

The EP properties were calculated through the pressure loss limit (p_{oz}) on a T-02U four-ball tribotester, following the ITeE-PIB Polish test method for testing lubricants under scuffing conditions [14]. This method measures the influence of lubricants on the propagation of scuffing and the intensity of wear through the wear scar diameter (WSD). Also, the frictional torque of the greases was measured, with 10 N.m being where the lubricant film breaks in the tribosystem; seizure load (P_{oz}) occurs at 10 N.m. The tests were performed with the following parameters: 3600s, 500 rpm, and a load varying from 0 to 7200 N in 18 s. WSD was calculated by averaging the diameter of the scars on the three fixed balls measured by SEM. Finally, p_{oz} was calculated by Equation 1:

$$p_{oz} = P_{oz}/(WSD)^2 \quad (1)$$

2.2. Anti-wear test (AW)

The AW properties of the greases were characterized with a four-ball tribotester (T-02U). The tribosystem consists of three stationary balls fixed in the ball pot with a required load (P) applied to an upper ball. The top ball is fixed in the ball chuck and rotates at a defined speed (n) in a perpendicular axis to the three fixed balls. The balls' material was an AISI 52100 steel. The AW properties were measured according to ASTM D 2266 in order to obtain the wear scar diameter (WSD), following the testing conditions of: 40 kgf, 1200 rpm, and 60 min at 75 °C. WSD was calculated by the average diameter of the scar on the three fixed balls measured by Scanning Electron Microscopy (SEM).

2.3. Ball-on-disk test

Additionally, a ball-on-disk tester (T-11) was used according to ASTM G-99 to determine the wear mass loss and COF for a pair of materials; one of them is the stationary ball pressed at the required load (P) against the disk that must be rotating at a certain speed (n). Testing parameters were: a sliding speed of 100 rpm, time of 60 min, track radius of 3 mm and a load of 5 kgf. Resin reinforced with 20 wt.% of glass fibres used for circuit breaker components were machined in square pieces to set them up on the disk specimen observed in Fig. 1. Ball materials were of an AISI 52100 steel with an R_a of 0.410 µm. For the glass fibre reinforced resin samples, the R_a value was 0.336 µm.

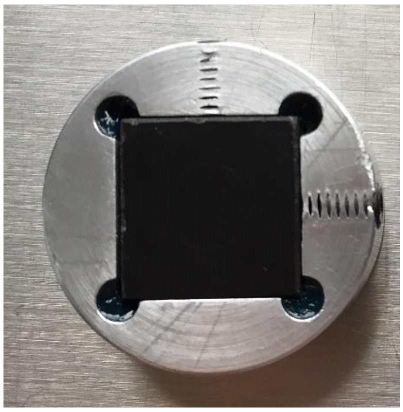


Fig. 1. Disk specimens with glass fibre reinforced resins prepared for ball-on-disk tests (T-11).

3. RESULTS

3.1. Extreme pressure test (EP)

Figure 2 shows the load-carrying capacity of the selected greases in N/mm^2; here, the highest performance was observed for grease 4, followed by greases 6 and 7.

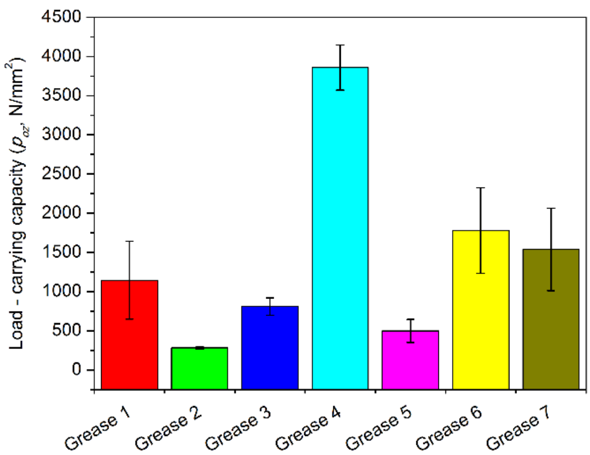


Fig. 2. Load-carrying capacity (p_{oz}) results obtained by the extreme pressure test.

In Figure 3, the WSD images obtained by SEM are shown. Here, the smaller scars resulted in higher p_{oz}, providing higher protection under EP conditions. The small WSD and high p_{oz} value for the EP test observed for grease 4 may be attributed to the high viscosity of its base oil (510 cSt) and its high working temperature range that allows for a lubricant film to be present between the ball materials avoiding metal-metal contact.

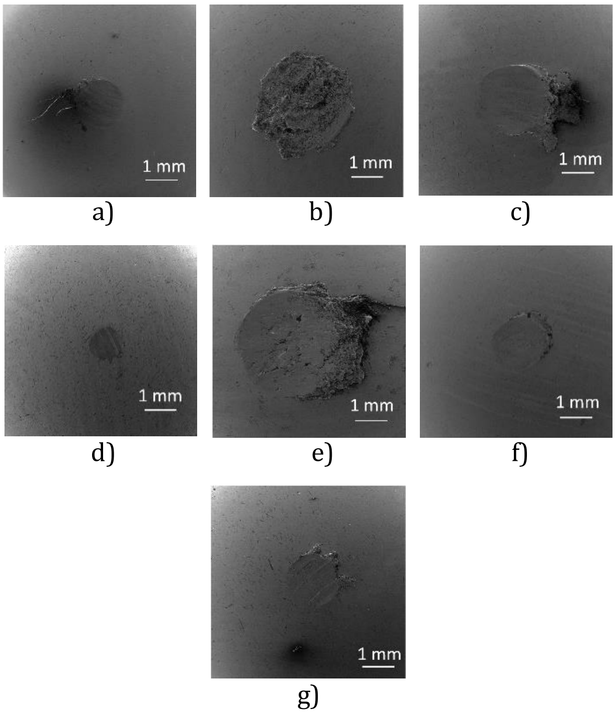


Fig. 3. Micrographs of wear scar diameters for the EP test: a) Grease 1; b) Grease 2; c) Grease 3; d) Grease 4; e) Grease 5; f) Grease 6; g) Grease 7.

3.2. Anti-wear test

Figures 4 and 5 show the micrographs of worn balls and WSDs measured by SEM for the anti-wear test.

In Figures 4 and 5, greases that showed the best performance on anti-wear tests were grease 7 and 6 with average values of ~0.45 mm, and 0.62 mm respectively. It may be noted that these greases contain a lithium thickener and also have high base oil viscosity (220 cSt), as shown in Table 1. A similar behaviour was found by Kanazawa et al. [4]. He prepared model greases thickened with lithium varying the base oil viscosity and concluded that the interaction between the base oil and thickener are the prevalent factors that determine their tribological performance. At low speeds the type of thickener determines the lubricant film thickness. However, at high speeds (similar to the conditions of our tests) the thickness of the lubricant film strongly depends on the viscosity of the base oil.

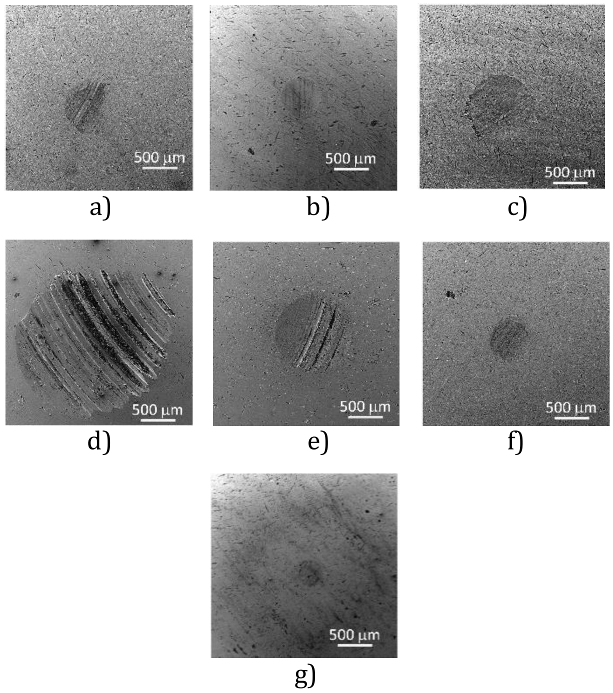


Fig. 4. Micrographs of wear scar diameters of greases obtained by SEM for the AW test. a) Grease 1; b) Grease 2; c) Grease 3; d) Grease 4; e) Grease 5; f) Grease 6; g) Grease 7.

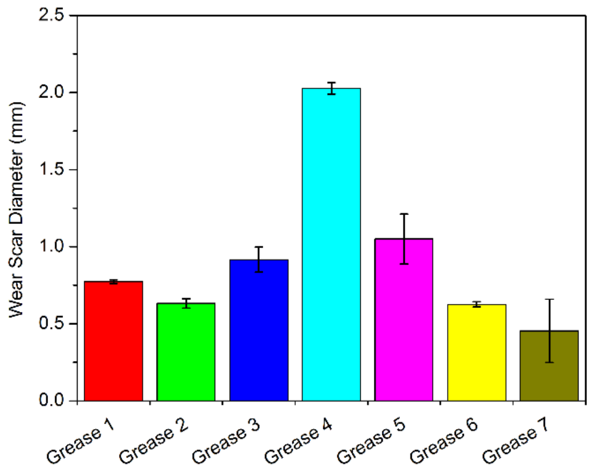
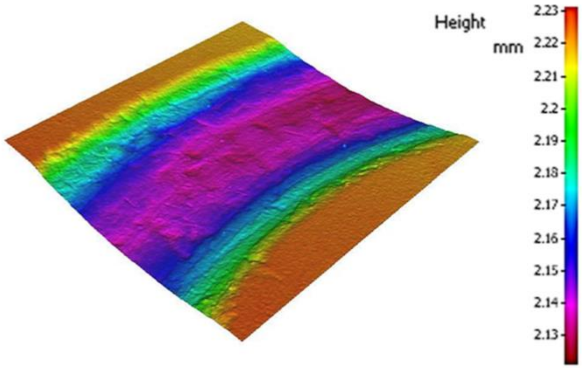


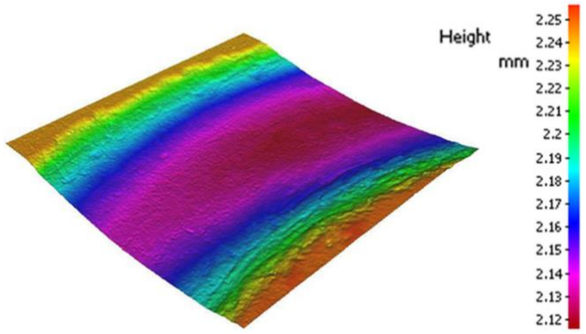
Fig. 5. Wear scar diameters in the anti-wear test according to ASTM D 2266.

3.3. Ball-on-disk test

In the ball-on-disk test, wear mass loss was measured for all test specimens in mg by weighting them before and after each test. The worn surfaces were analysed by a 3D surface analyser measurement system. In Figure 6 the 3D images of the wear tracks of grease 1(Fig. 6a), grease 2 (Fig. 6b), and grease 6 (Fig. 6c) are shown. Here, smaller wear tracks are indicative of better grease performance that limited material contact during the wear test.



a)



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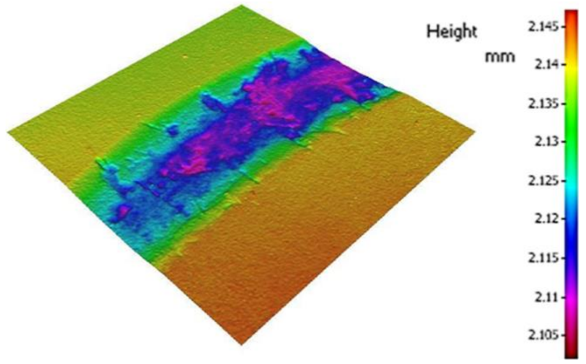

c)

Fig. 6. Wear tracks of disks from the ball-on-disk test. a) Grease 1; b) Grease 2; c) Grease 6, (size of 2x2 mm each).

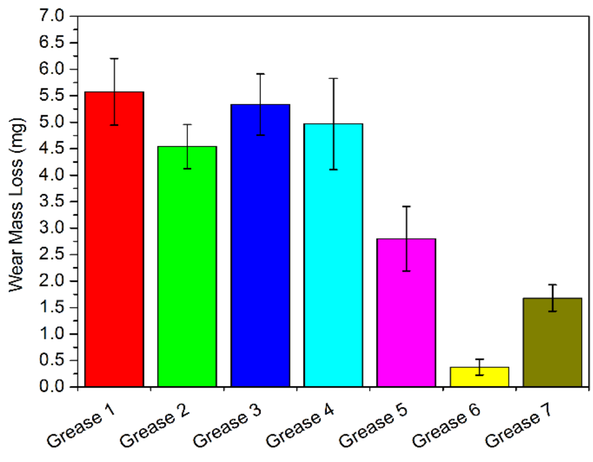

Fig. 7. Results of wear mass loss of the test specimens in ball-on-disk tests.

As depicted in Fig. 7, grease 6 (with a lithium thickener) showed the best results with the lowest wear mass loss (0.4 mg) as evidenced by the smaller wear track width shown in Fig. 6c. Furthermore, it presented a low standard deviation, providing greater lubrication reliability. Grease 7, also with a lithium thickener, provided excellent anti-wear protection, with a wear mass loss of 1.68 mg. As explained by De Laurentis et al. [5], at low speeds lithium thickeners in greases form a thicker film providing better tribological protection.

In Figure 8 COF values obtained by the ball-on-disk tests are presented.

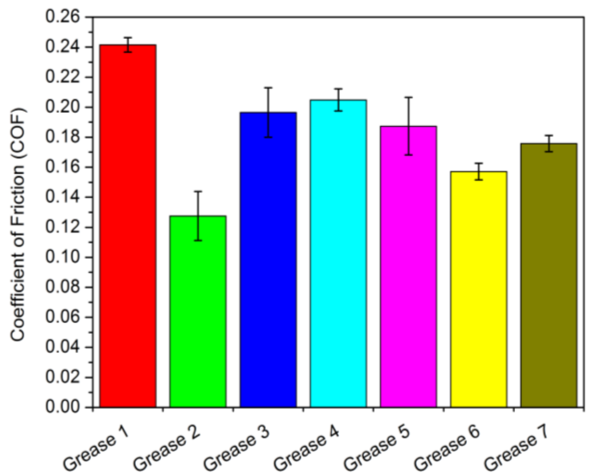

Fig. 8. Coefficient of friction (COF) results obtained by ball-on-disk test.

Here, results ranged from 0.12 – 0.24 for all greases, with grease 2 showing the lowest COF. The behaviour found for this grease can be explained by the homogeneous surface and the lack of craters and/or traces of adhesive wear on the wear track (Fig. 6b), compared to grease 1 (Fig. 6a) and grease 6 (Fig. 6c).

3.4. Durability test in circuit breakers (testing bench)

In the electrical industry safety tests are performed for industrial circuit-breakers. This ensures that circuit-breakers support a certain number of operating cycles without losing the ability to interrupt the current flow. The durability test performed in this study consisted on simulating its operation process by turning the circuit-breaker off and on in a testing bench for 10,000 cycles during 48 h.

For the durability test, grease 4, grease 6 and grease 7 were selected due to the tribological performance shown on laboratory tests under AW (greases 6 and 7) and EP conditions (grease 4).

During the durability tests a wear track perimeter was generated on the circuit breaker cover (Fig. 9a). This wear was caused by the contact between the internal components of the circuit breaker where the greases were applied. The circuit breaker cover was extracted from the case to analyse the wear track at the end of each test. The profiles of the worn area of the case were measured using a 3D surface analyser. Representative wear tracks, wear profiles, and worn area measurements are shown in Figs. 9b, 9c, and 9d, respectively.

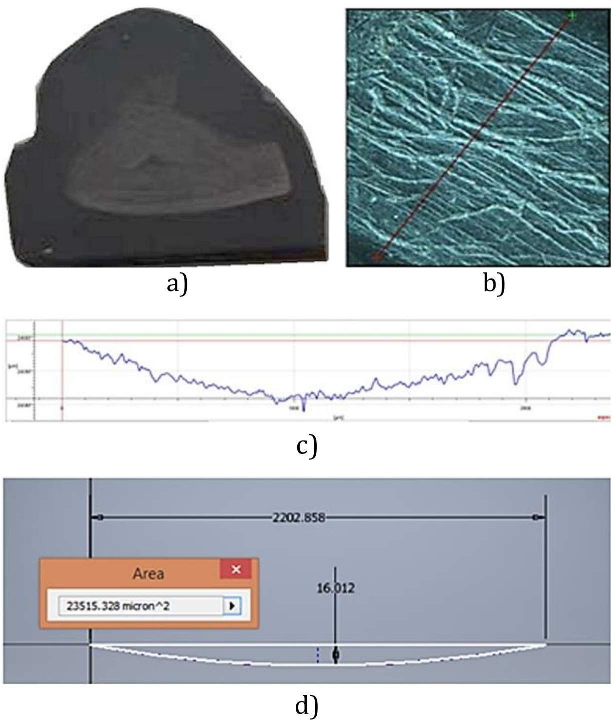

Fig. 9. a) Circuit breaker cover wear track perimeter; b) wear track; c, d) wear track profile.

Comparisons of the worn cases are shown in Fig. 10, where the worn area is highlighted in red. Here, it is evident that grease 6 provided the best tribo-characteristics of COF and wear protection on the circuit breaker component.

It can be noted that grease 6 showed the lowest worn area, followed by grease 7, which is consistent with the results obtained by the AW tests performed with the four ball and the ball-on-disk tribotesters.

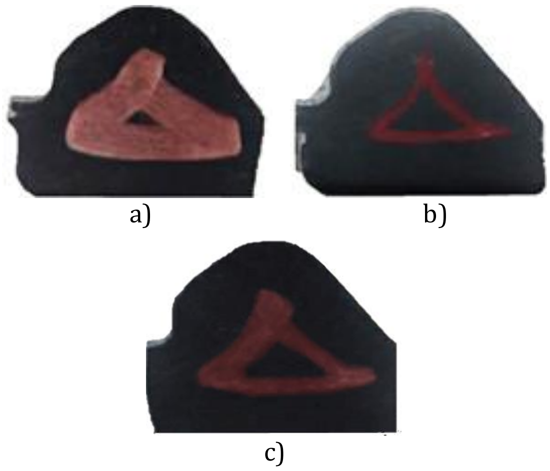

Fig. 10. Worn area obtained in circuit breaker components by the durability test a) Grease 4; b) Grease 6; c) Grease 7.

The worn area results in μm^2 are presented in Fig. 11.

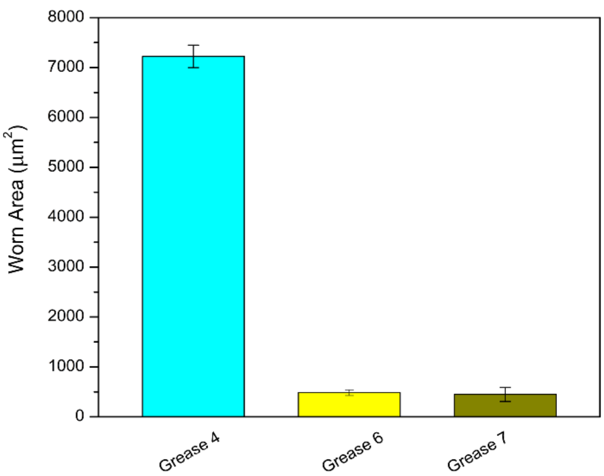

Fig. 11. Worn area of greases obtained by the durability test.

Although grease 4, which has EP additives in its formulation, showed excellent tribological properties under EP conditions, it did not perform well under the durability test. According to Canter [3], EP additives may not be required in some cases where the temperature of the system does not rise sufficiently to activate a specific additive, which is the case of circuit breakers. In this case, the additives were activated when the EP laboratory test was performed but were not activated during the durability test.

4. CONCLUSION

Selected commercial greases were evaluated to provide appropriate selection for their application in circuit breakers. In the EP tests, grease 4 had the best load-carrying capacity, followed by grease 6 and 7. For the anti-wear tests and ball-on-disk tests, the greases with the best performance were greases 6 and 7.

Based on these results, the greases 4, 6, and 7 were selected for the durability test in circuit breakers. The results of this test show that grease 6 provided the best results with the lowest worn area, thus providing a good alternative for the analysed circuit breakers. It is important to note that lithium thickened greases with a viscosity of 220 cSt have the best AW tribological properties in the laboratory and in the test field, which shows that viscosity is an important factor to consider for tribological applications on greases among the temperature range and the kind of thickener.

The importance of this work relies on reducing the time and costs incurred by the durability tests on the testing bench by applying a methodology that allows to identify the greases with the best tribological characteristics in a reduced scale.

Acknowledgement

The authors would like to acknowledge the valuable contributions by Luis Alberto-Carreón and Patricio García-Pineda.

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